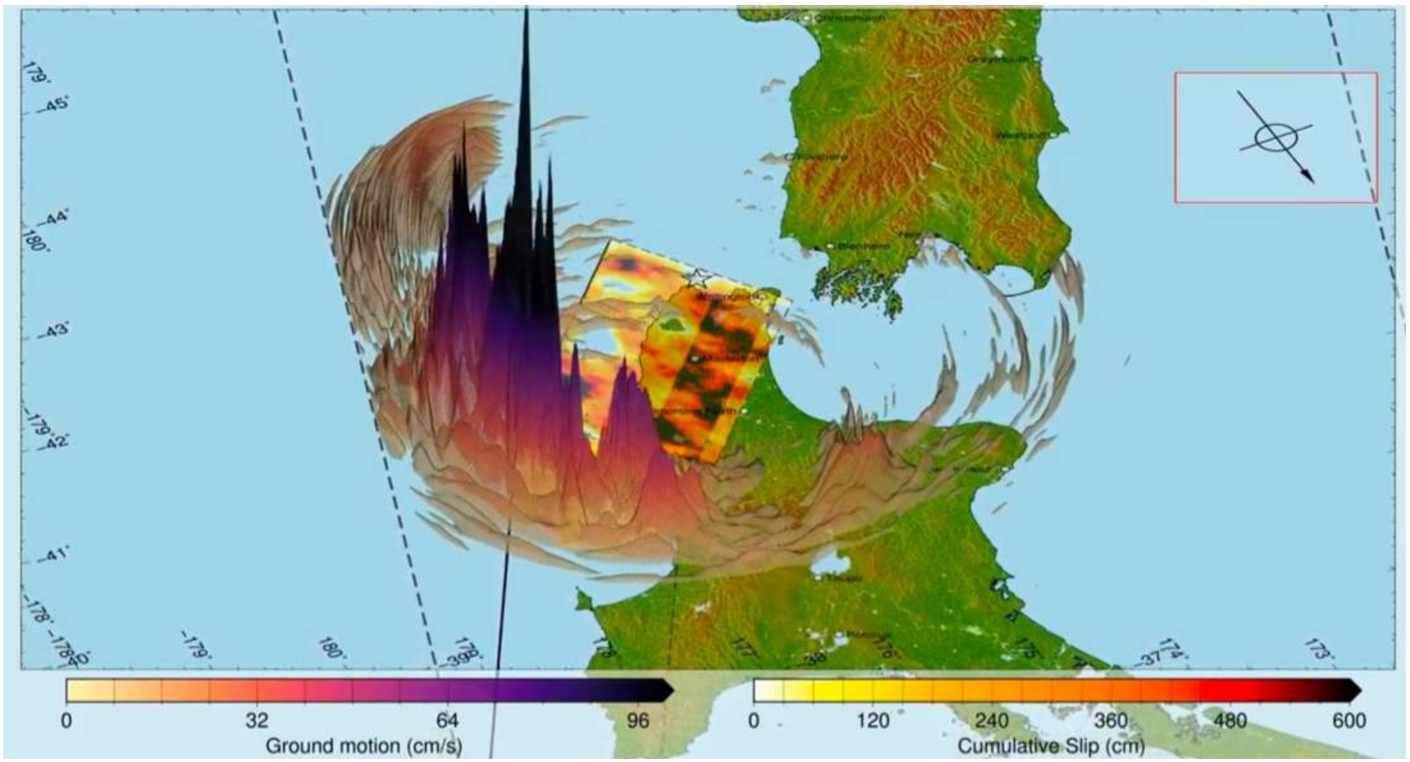
Observed ground motion basin amplifications and modelling for future events

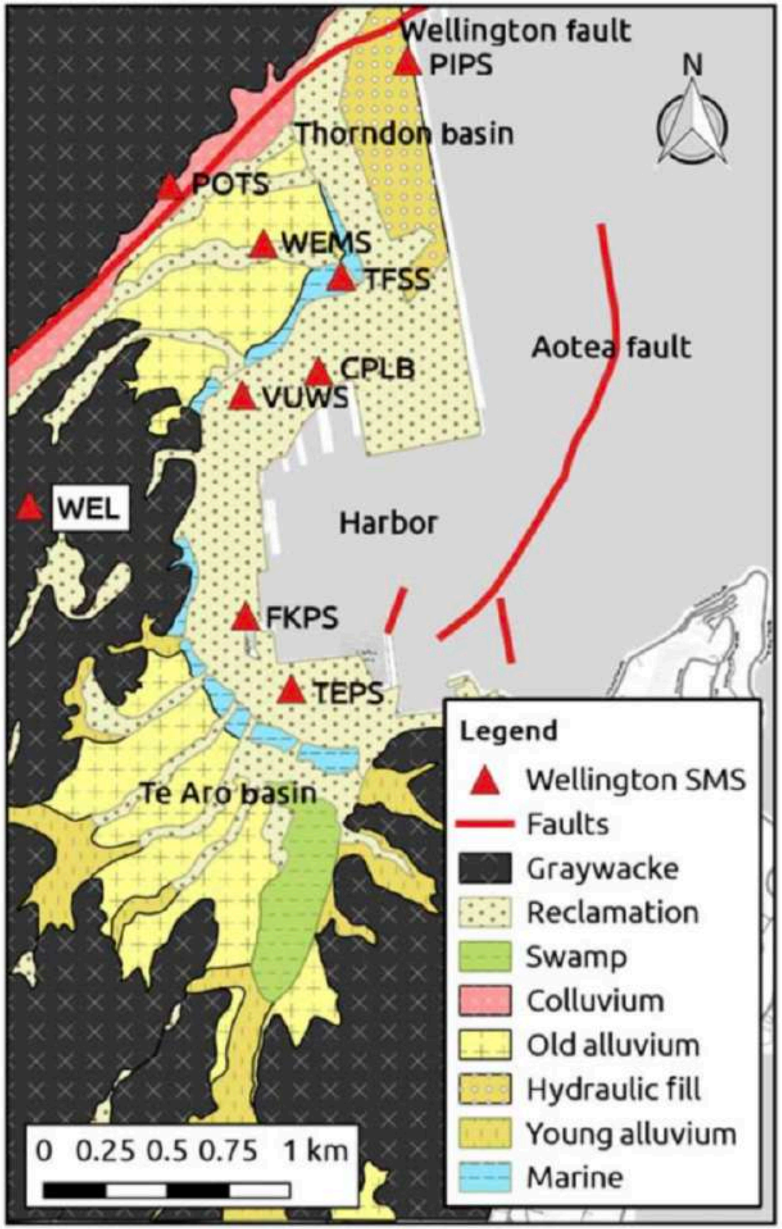


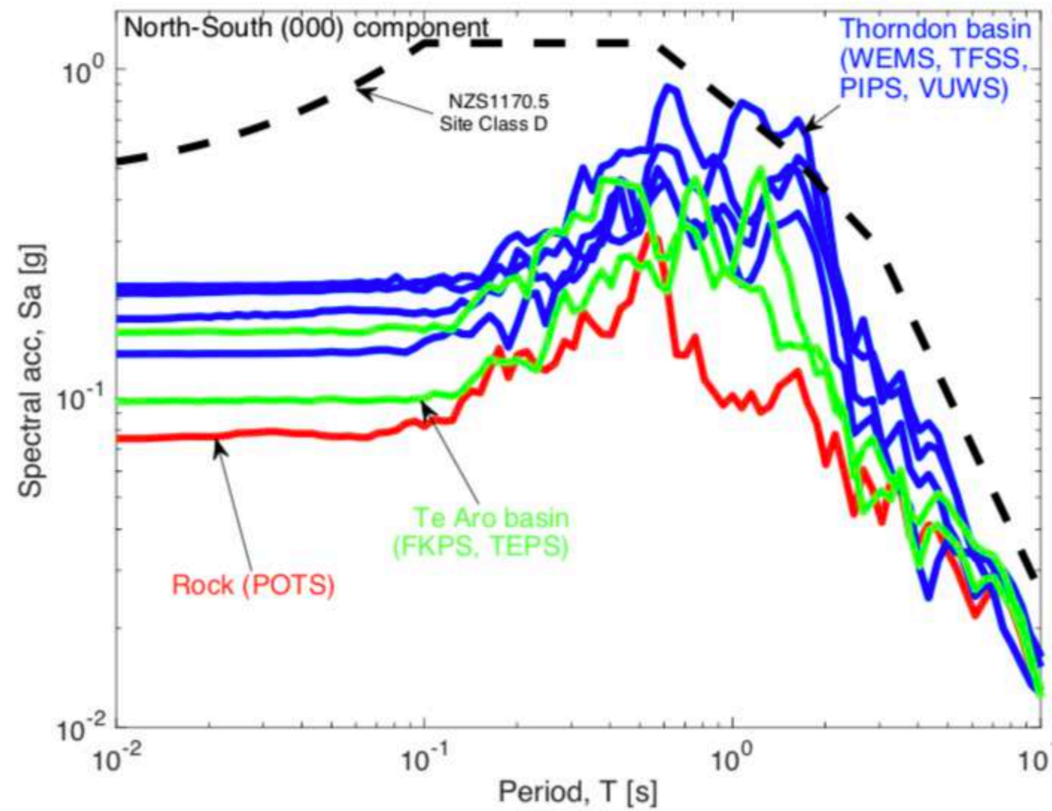
Brendon Bradley, University of Canterbury, New Zealand

Director, QuakeCoRE: The NZ Centre for Earthquake Resilience

What have we directly observed at Wellington ground motion stations in the 2016 Kaikōura, and other moderate magnitude, earthquakes?

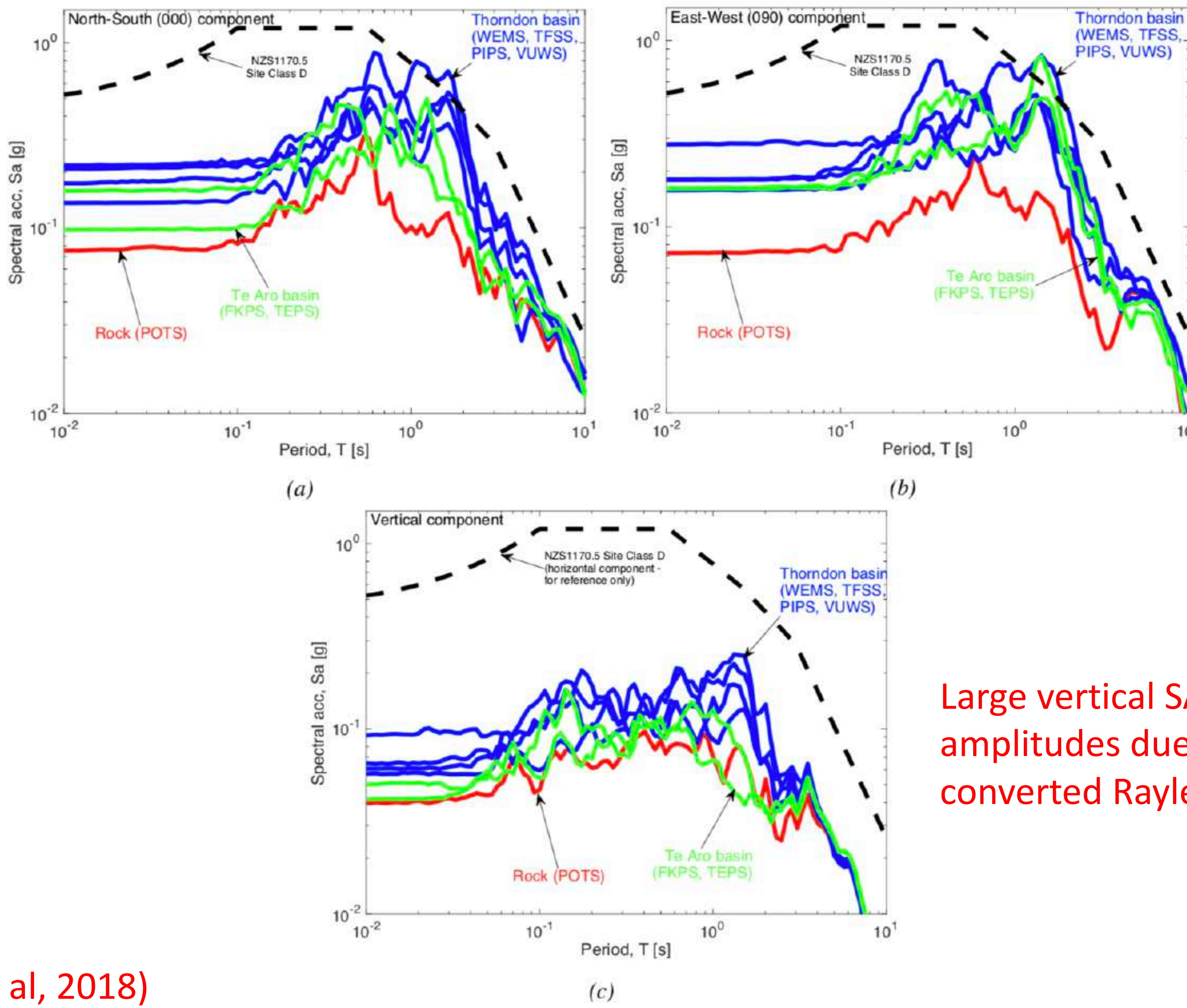
Observations – Kaikōura 2016





(Bradley et al, 2018)

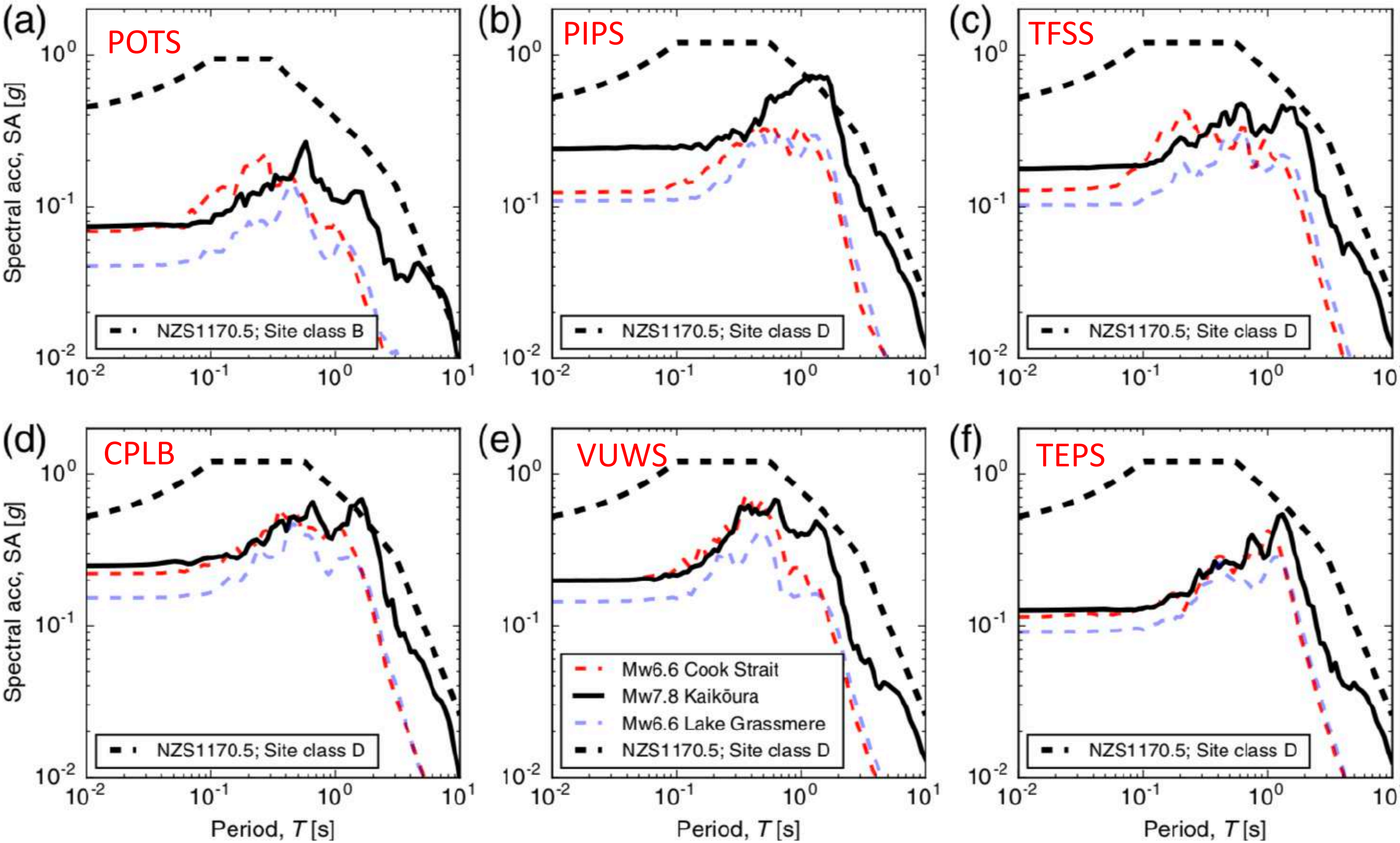
Observations – Kaikōura 2016



Large vertical SA(T~1.5) amplitudes due to converted Rayleigh waves

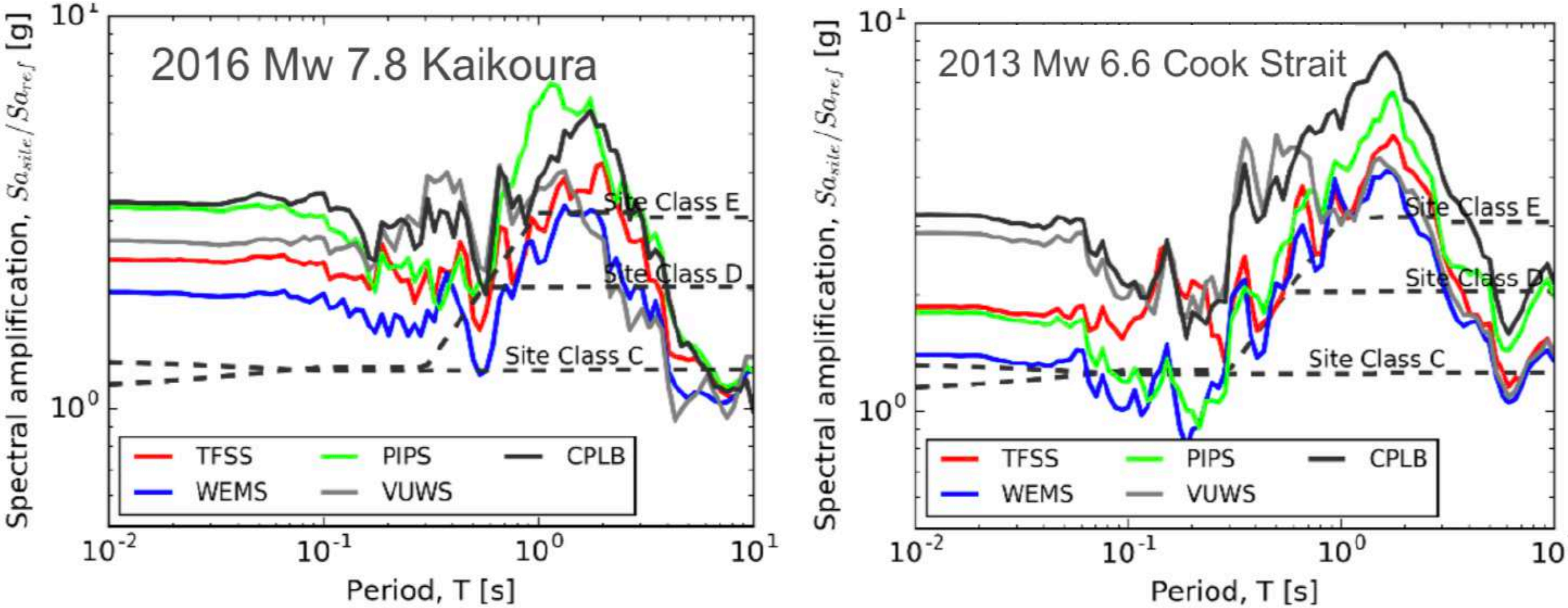
(Bradley et al, 2018)

Observations – multiple M>6 events



(Bradley et al, 2018)

Obs. Spectral ratios – Multiple events

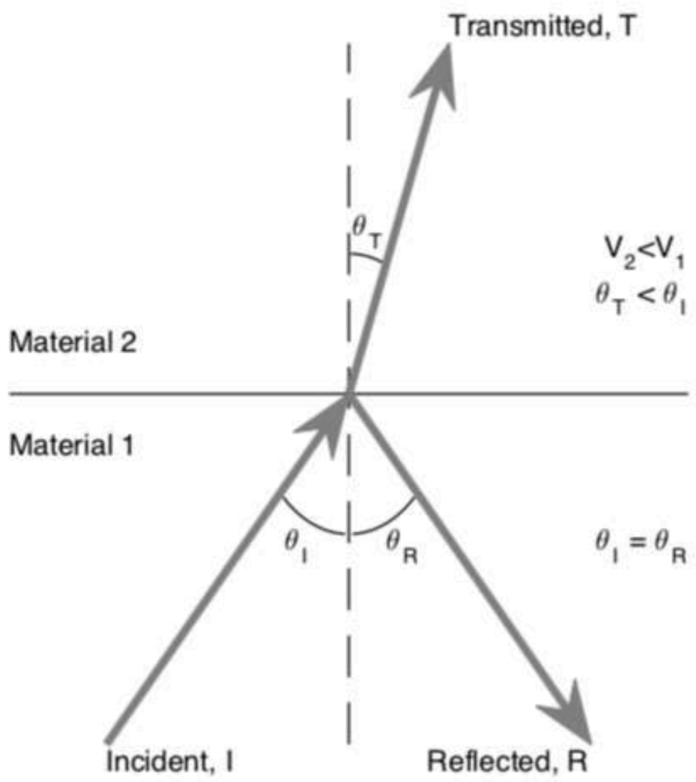


- Key trends:
  - For T~1.5s, amplifications, AF~3-7
  - For T>5s, AF~1
- The " Site C/D boundary discussion" in Wellington (based on geotechnical definitions) is detached from reality (the amplifications we actually observe)

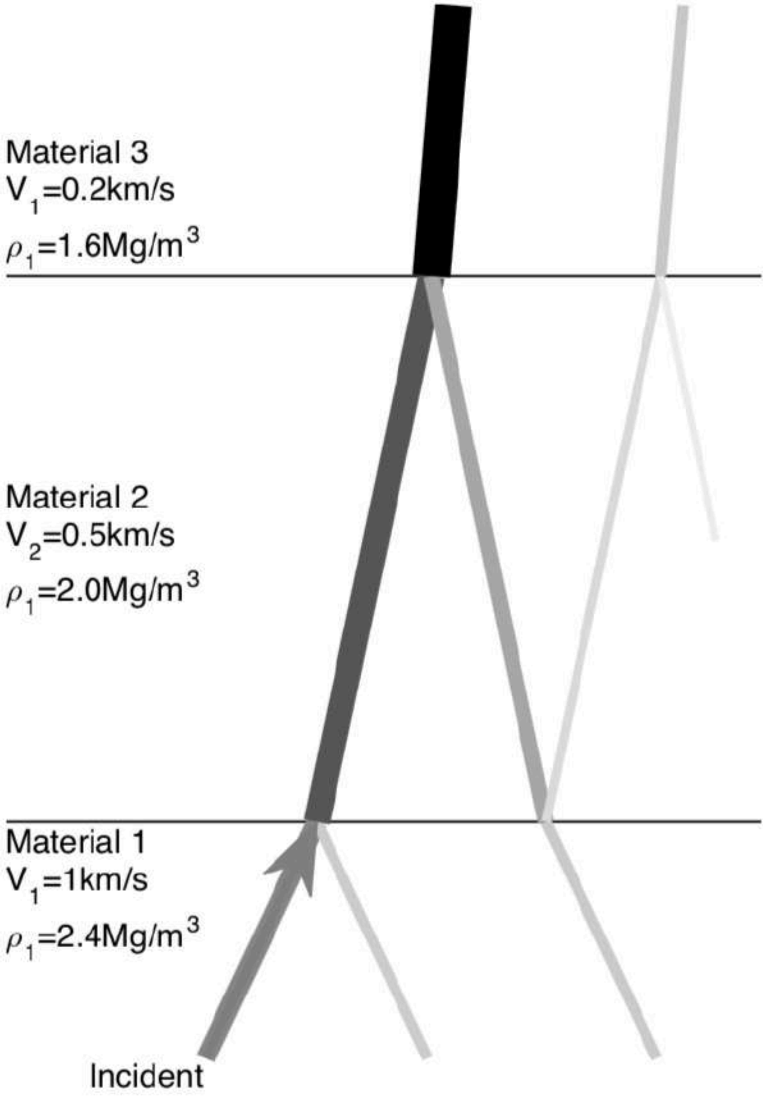
What are the salient phenomena that give rise to these observations at ’basin’ sites?

Reflection, refraction and impedance

Reflection and refraction of transmitted wave

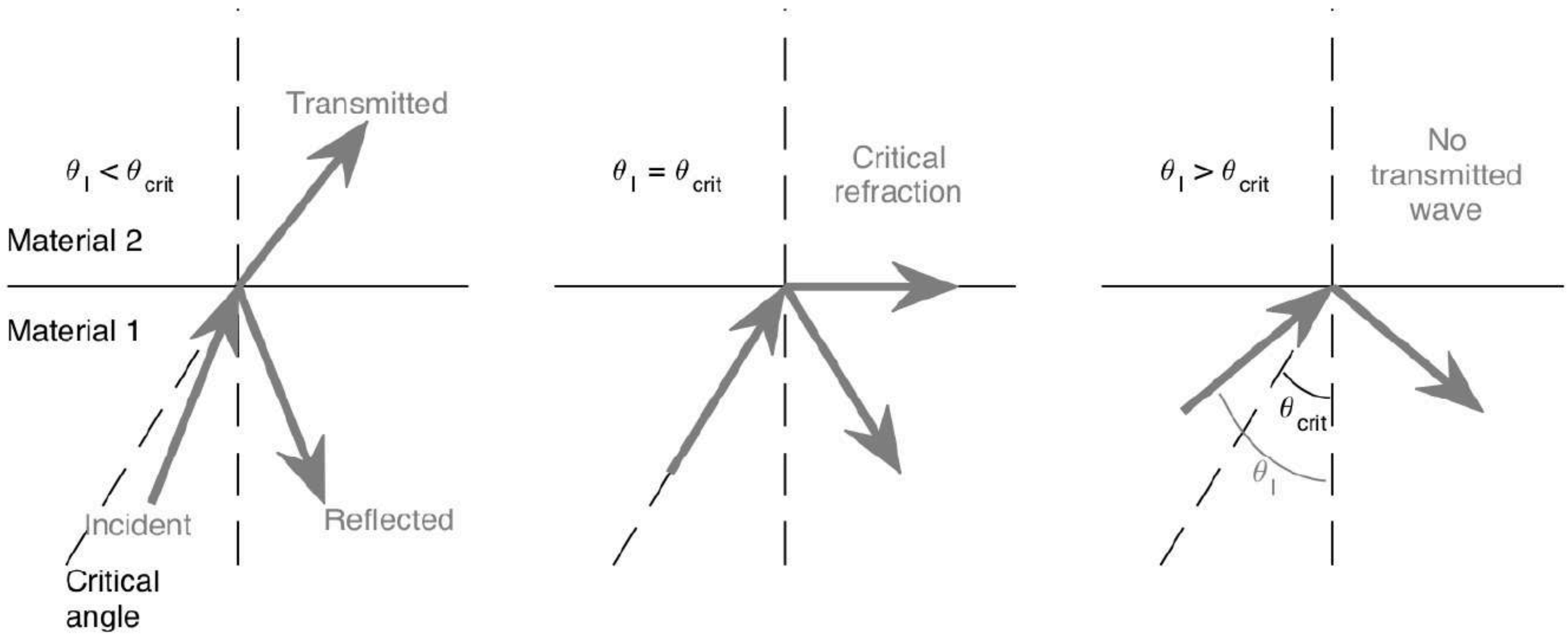


Effect of impedance (on amplitude) and multiple layers



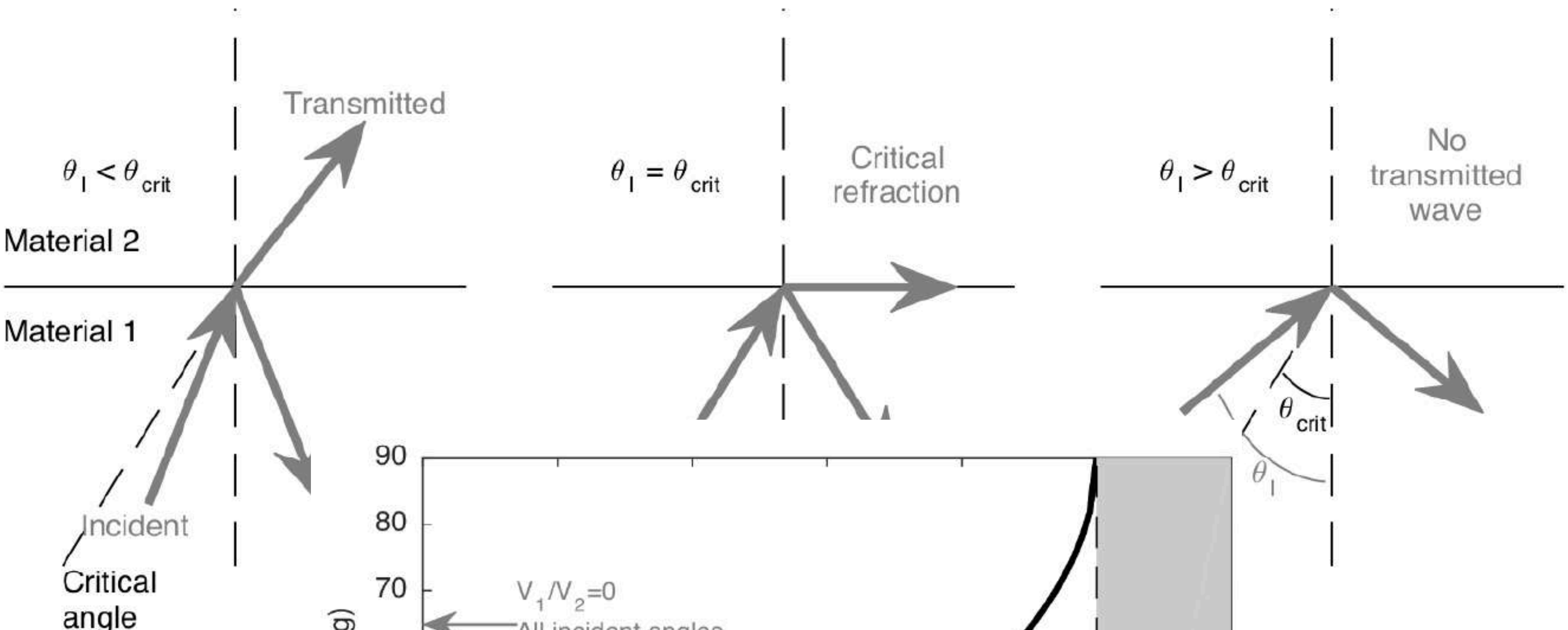
(Baker, Bradley, Stafford, 2020)

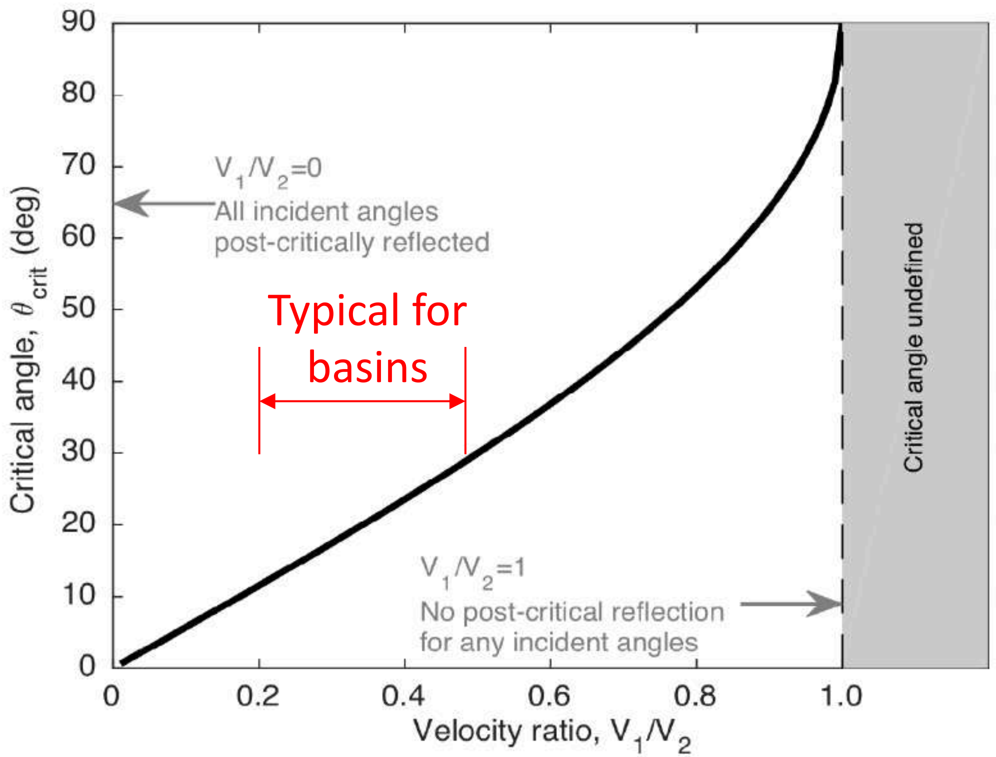
Critical refraction / total internal reflection



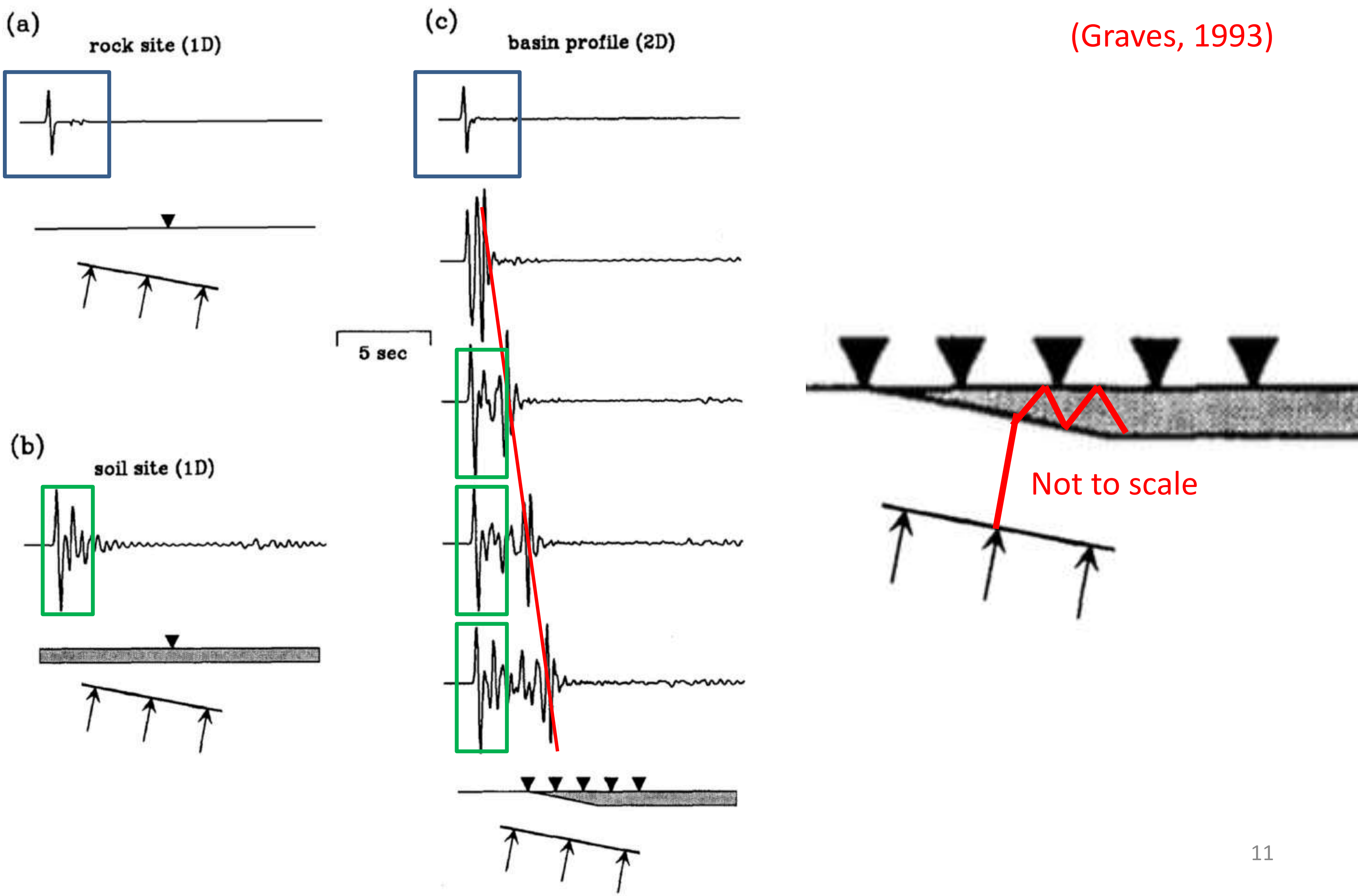
(Baker, Bradley, Stafford, 2020)

Critical refraction / total internal reflection





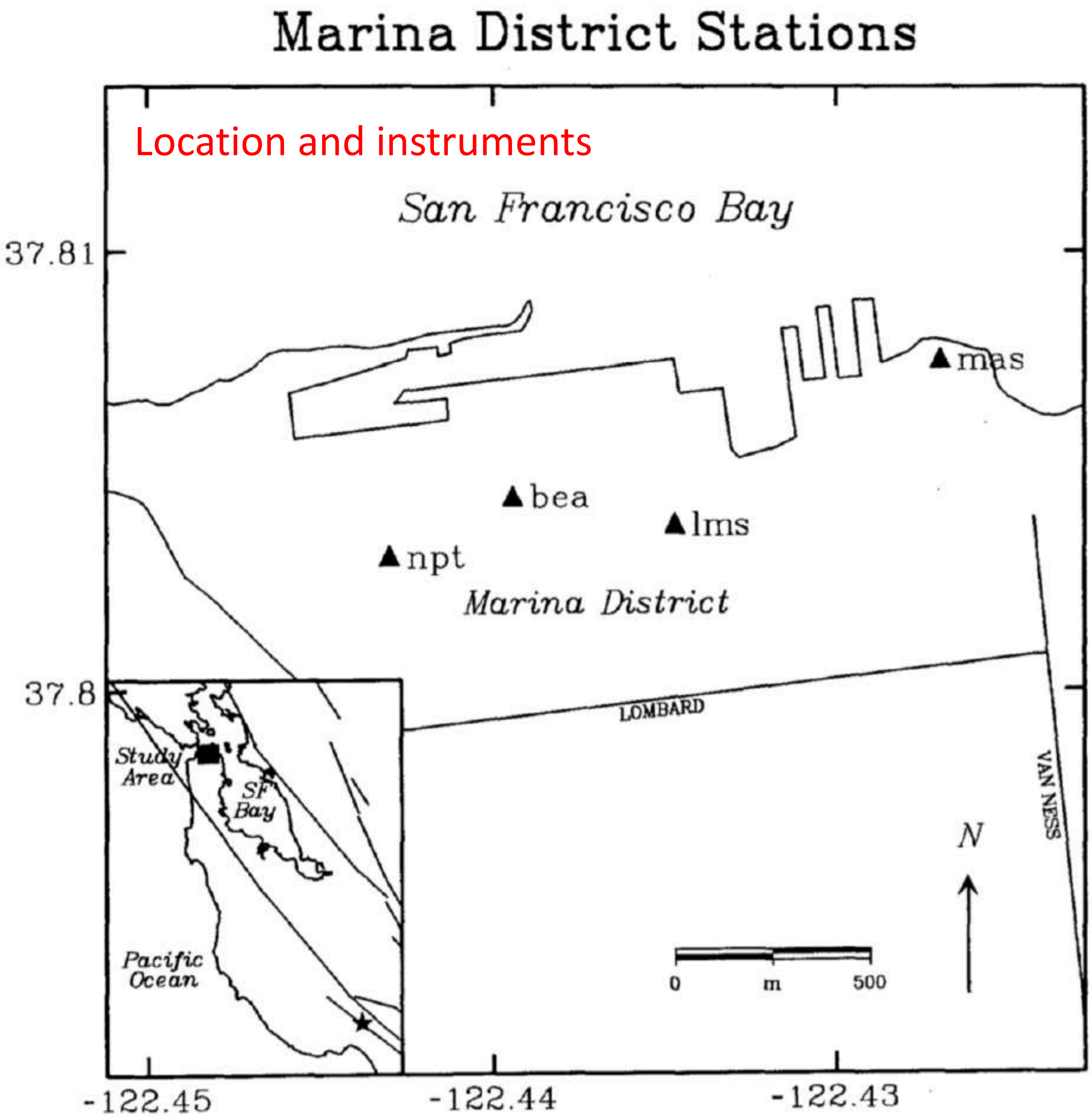
Impedance vs. basin-edge illustration



Historical examples of basin-edge effects

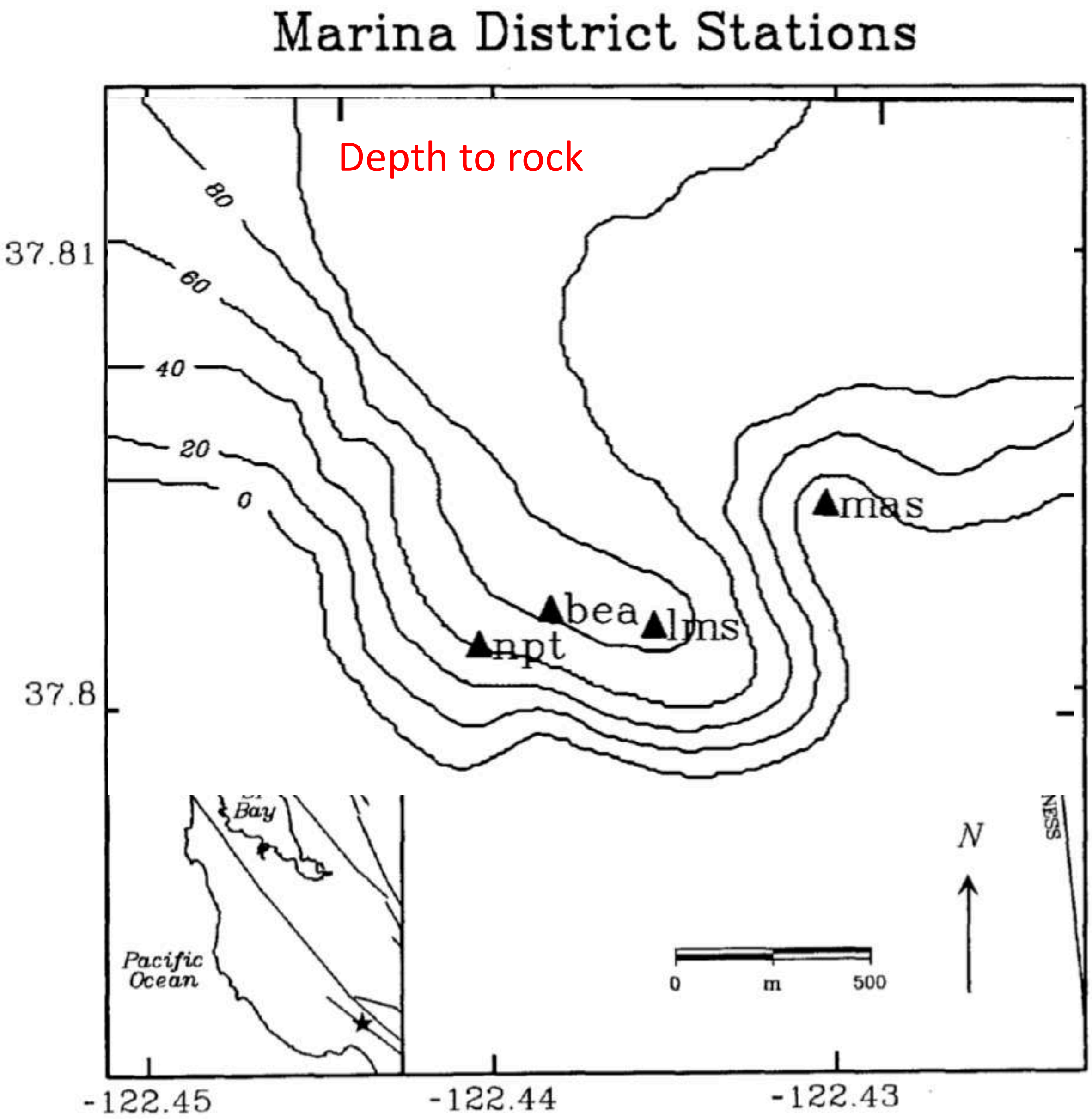
Loma Prieta (1989) – Marina District

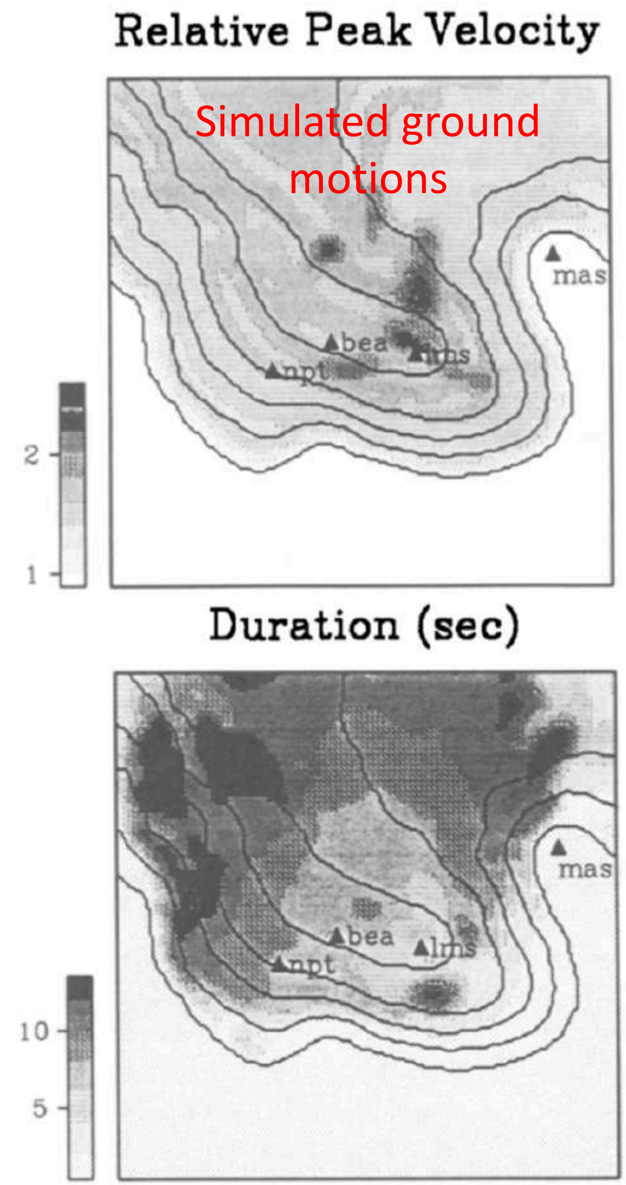
(Graves, 1993)



(Graves, 1993)

Loma Prieta (1989) – Marina District

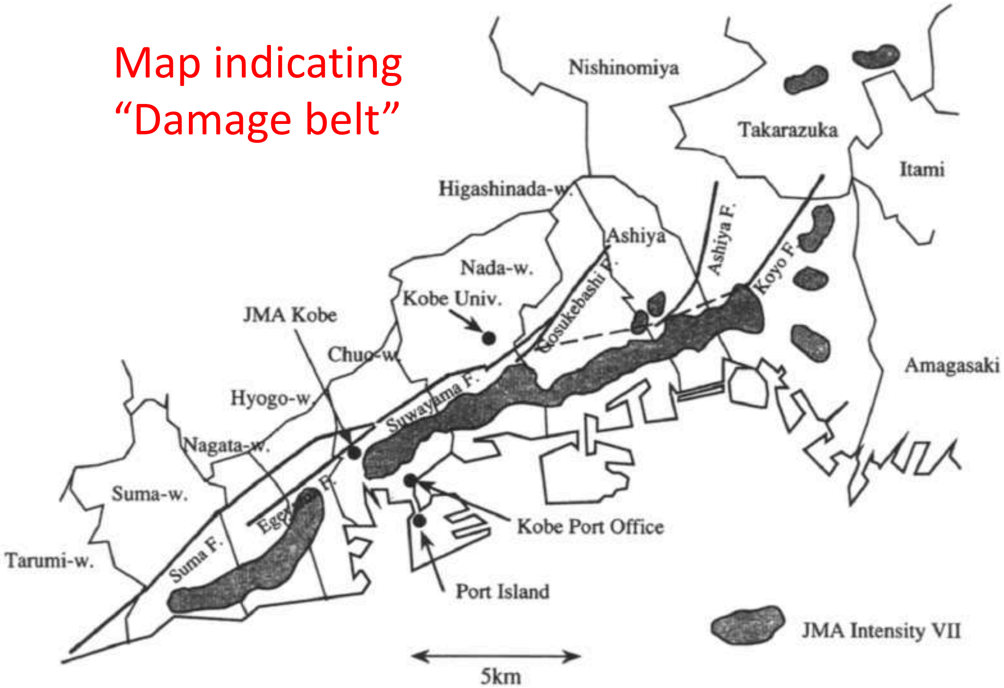




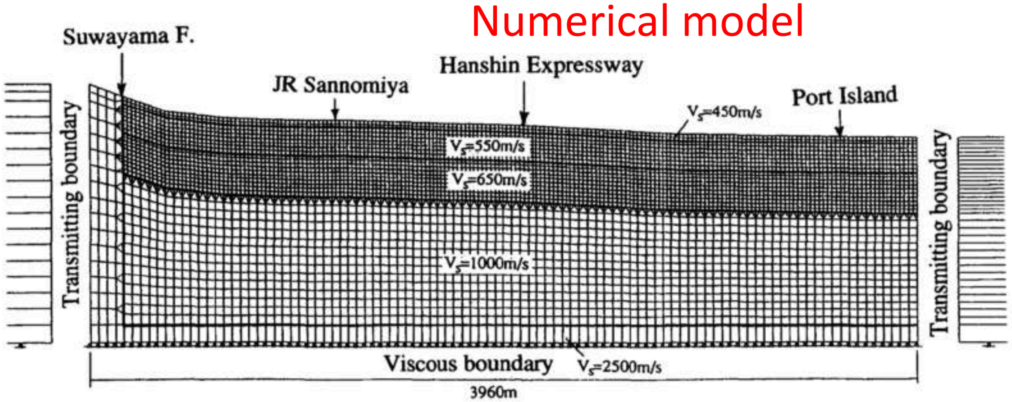
(Kawase, 1996)

Kobe (1995)

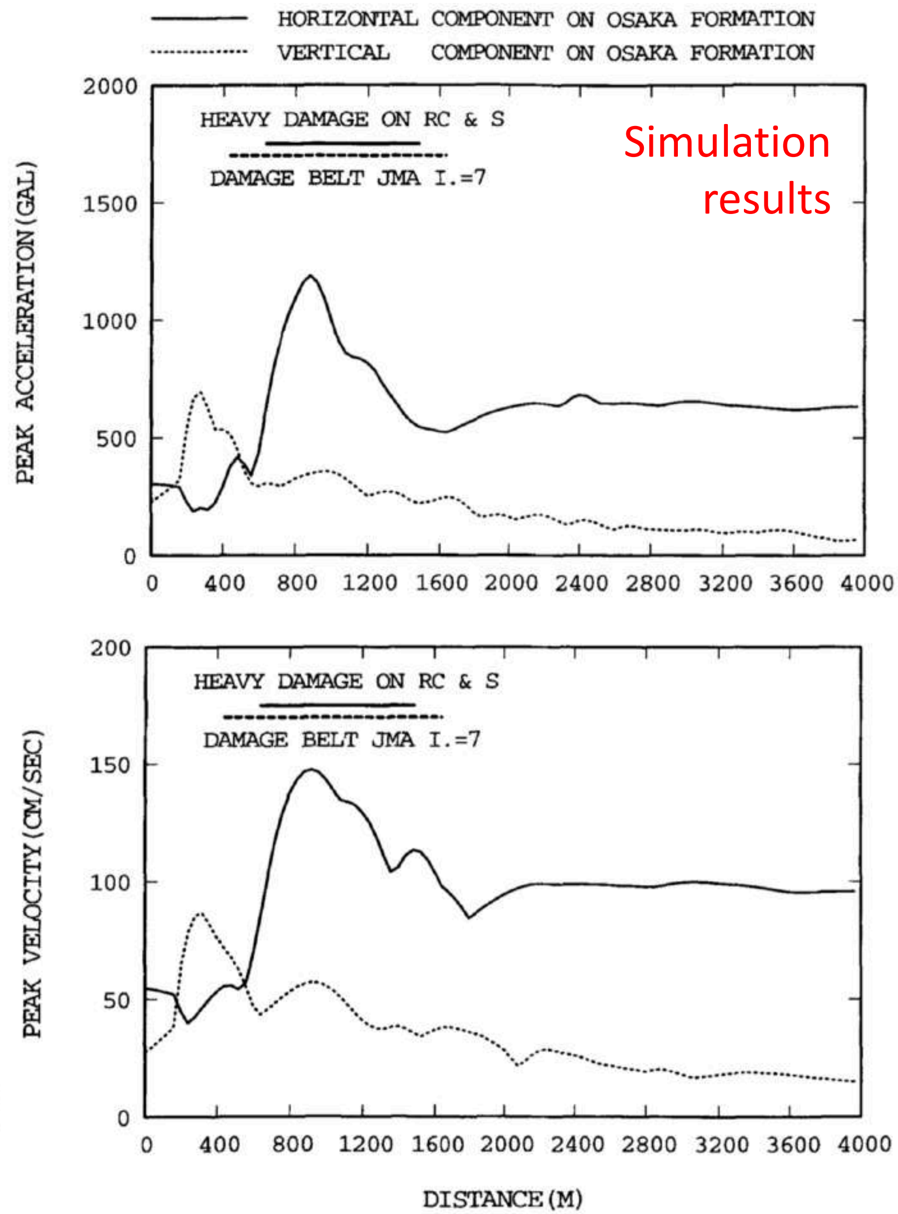
Map indicating "Damage belt"



Numerical model

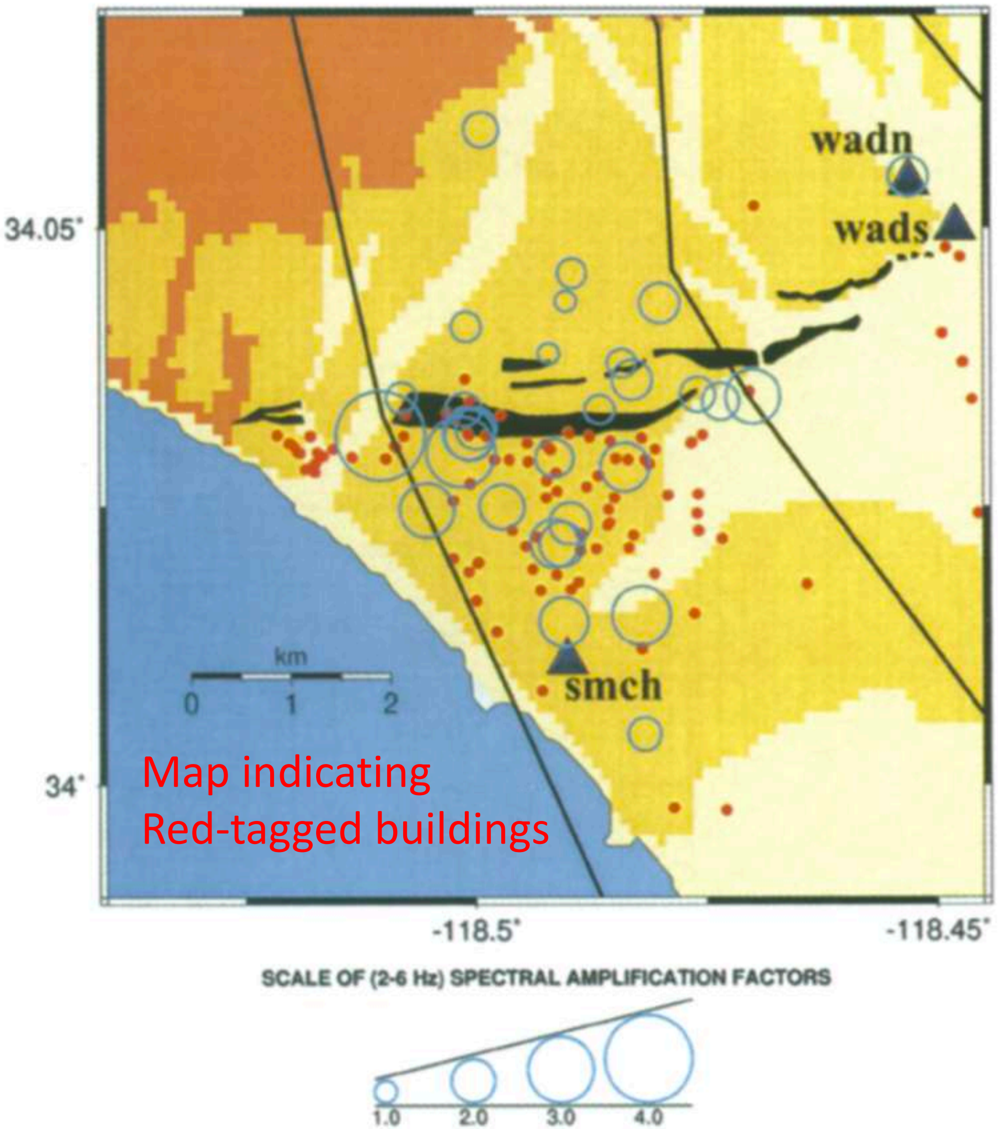


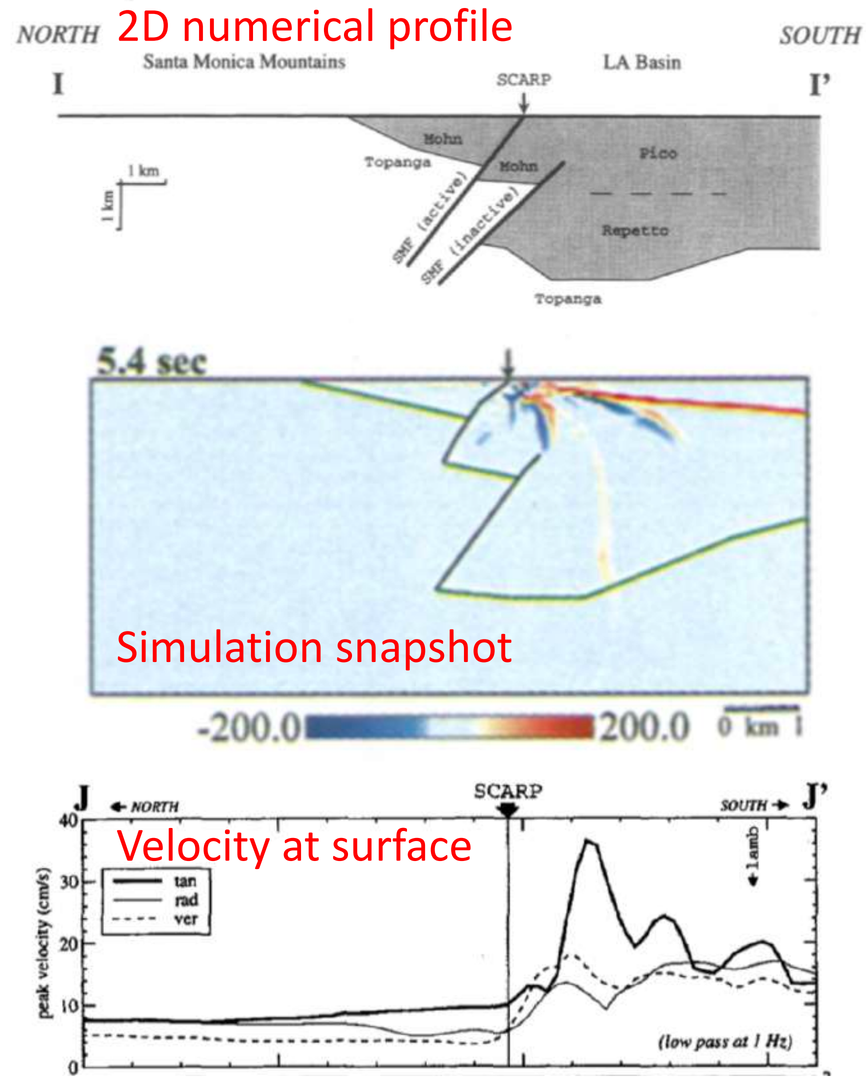
Simulation results



Northridge (1994) – Santa Monica

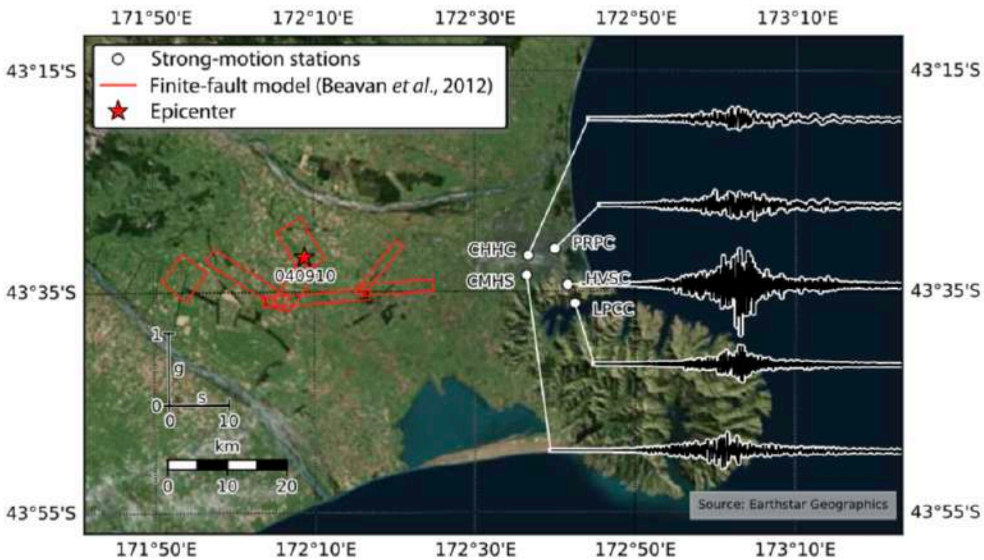
(Graves, 1998)

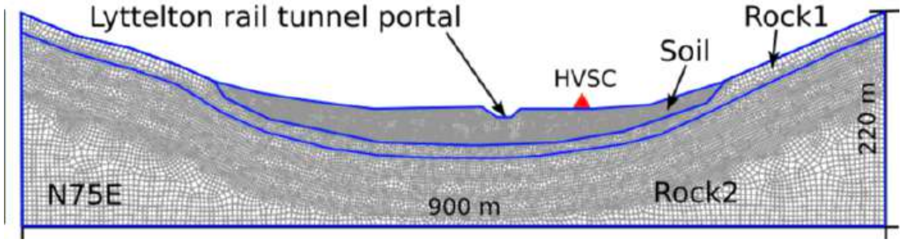


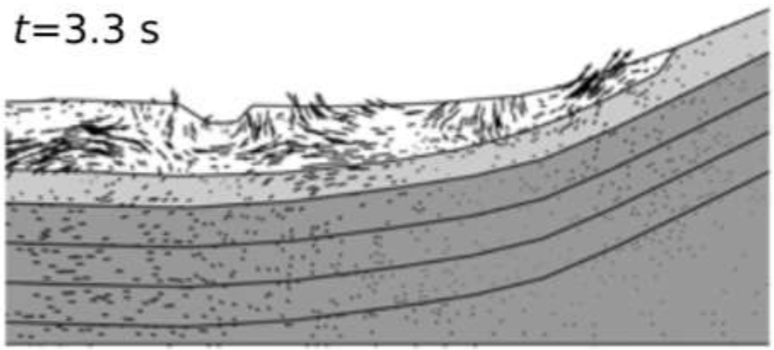


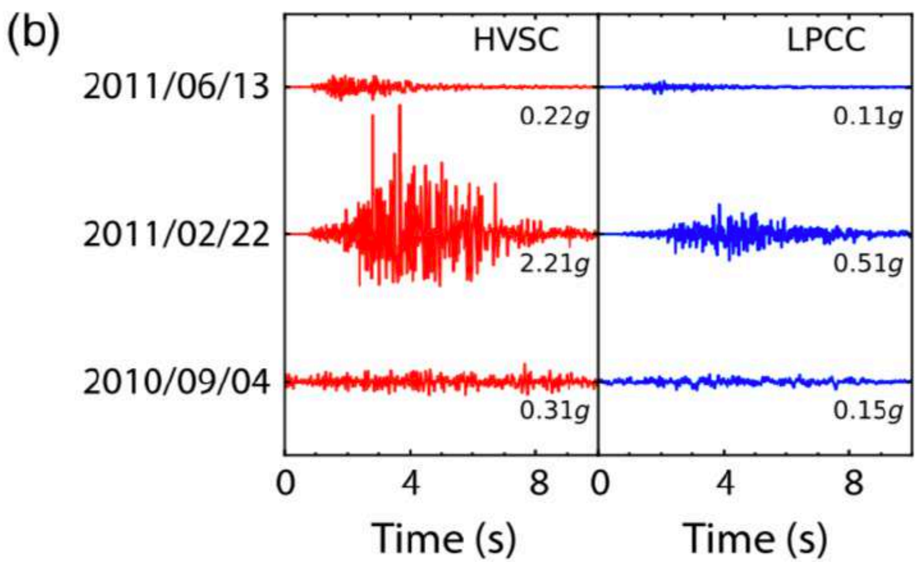
Canterbury (2010-2011) - Heathcote Valley

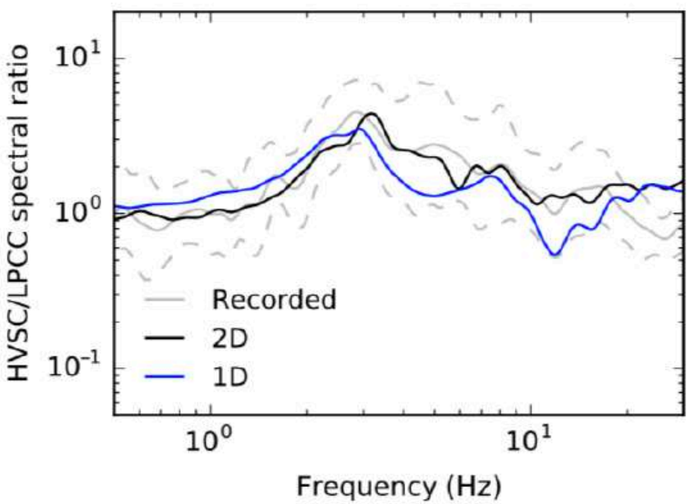
(Jeong et al, 2017)











How can we quantify these basin effects?

Quantification of ‘basin’ effects

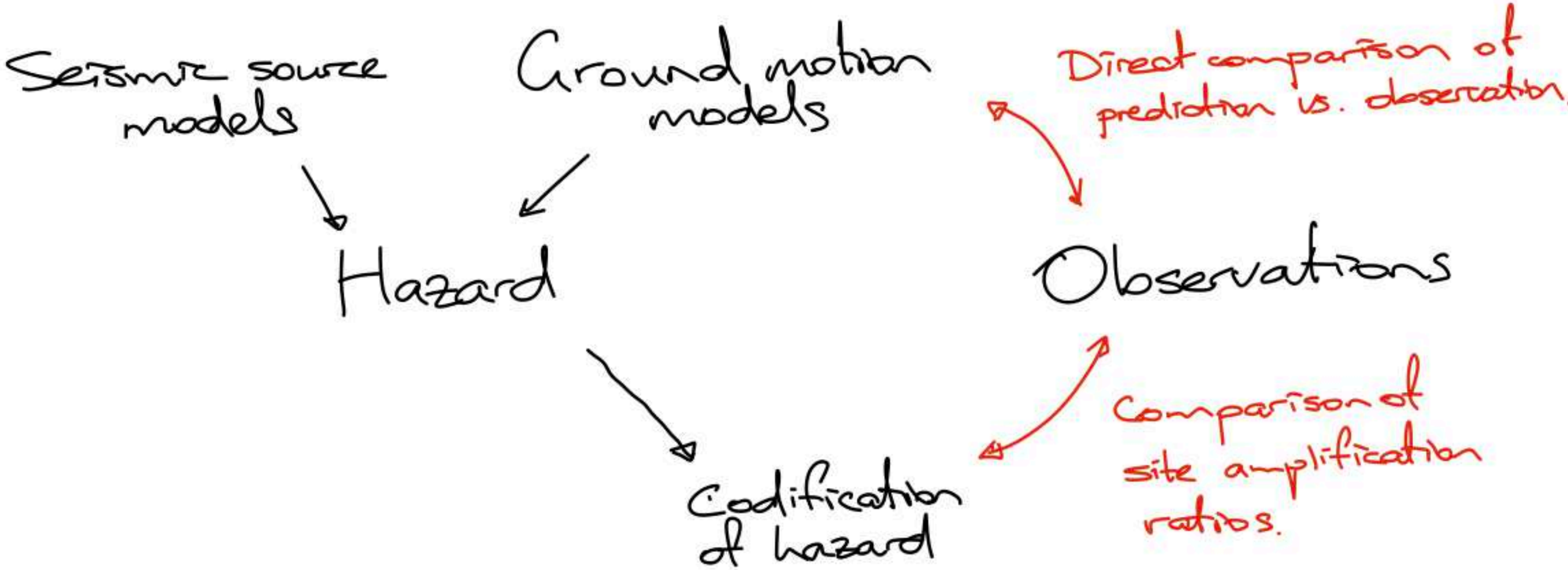
- Empirical representation
  - Direct modification of code-based spectral shapes
  - Modification of empirical ground motion models (that underpin code spectra)

Easier to develop; extrapolation problems (spatially within a region and for different regions; effects of source location relative to basin; consideration of ground motion amplitude)

- Physics-based representation
  - Simulations that explicitly model basin effects

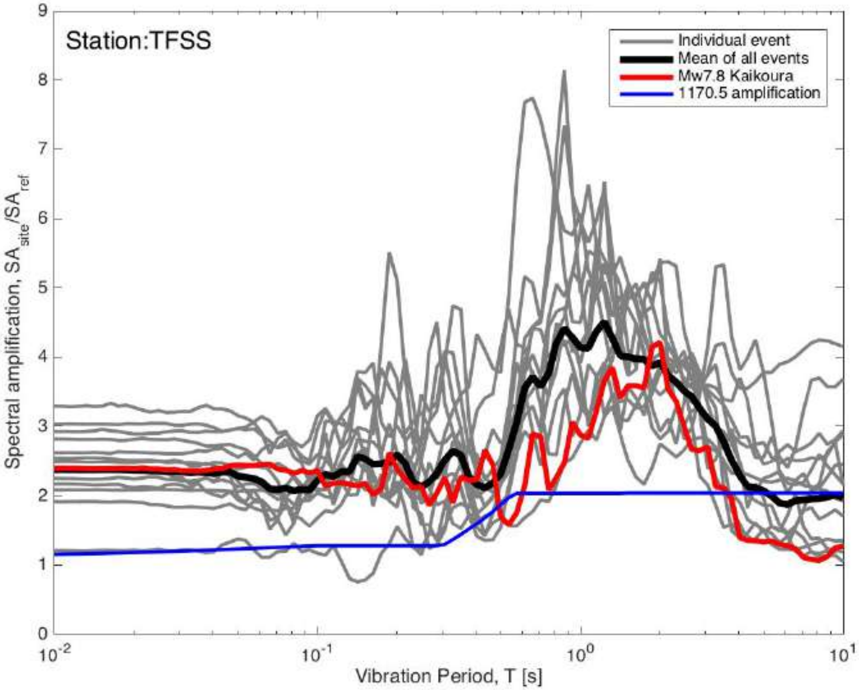
Harder to develop; more generalizable (physics provides framework for extrapolation)

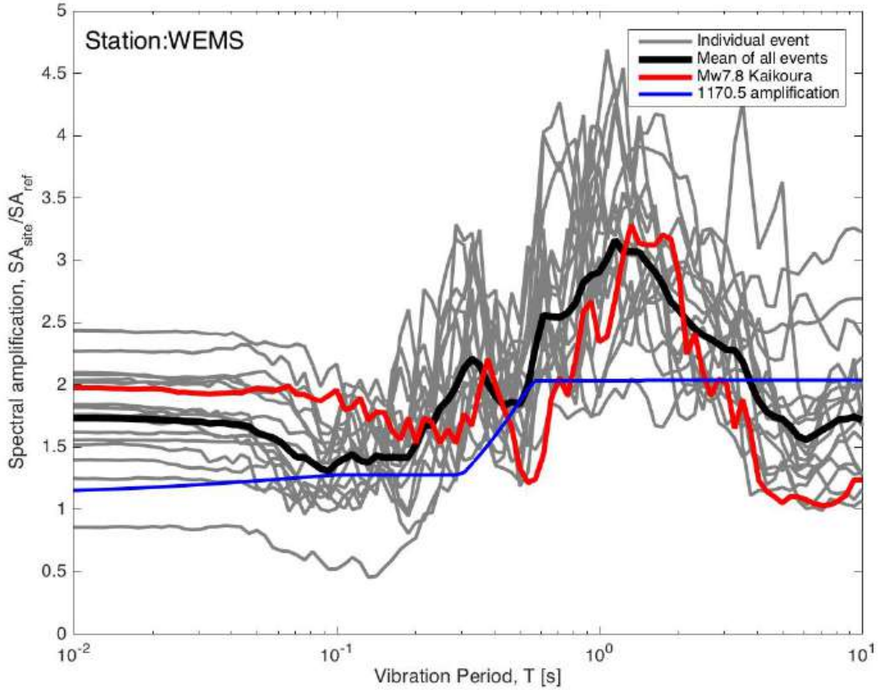
Empirical representation of basin effects



Adjustment factors for code-oriented utilisation

Code-oriented empirical adjustment

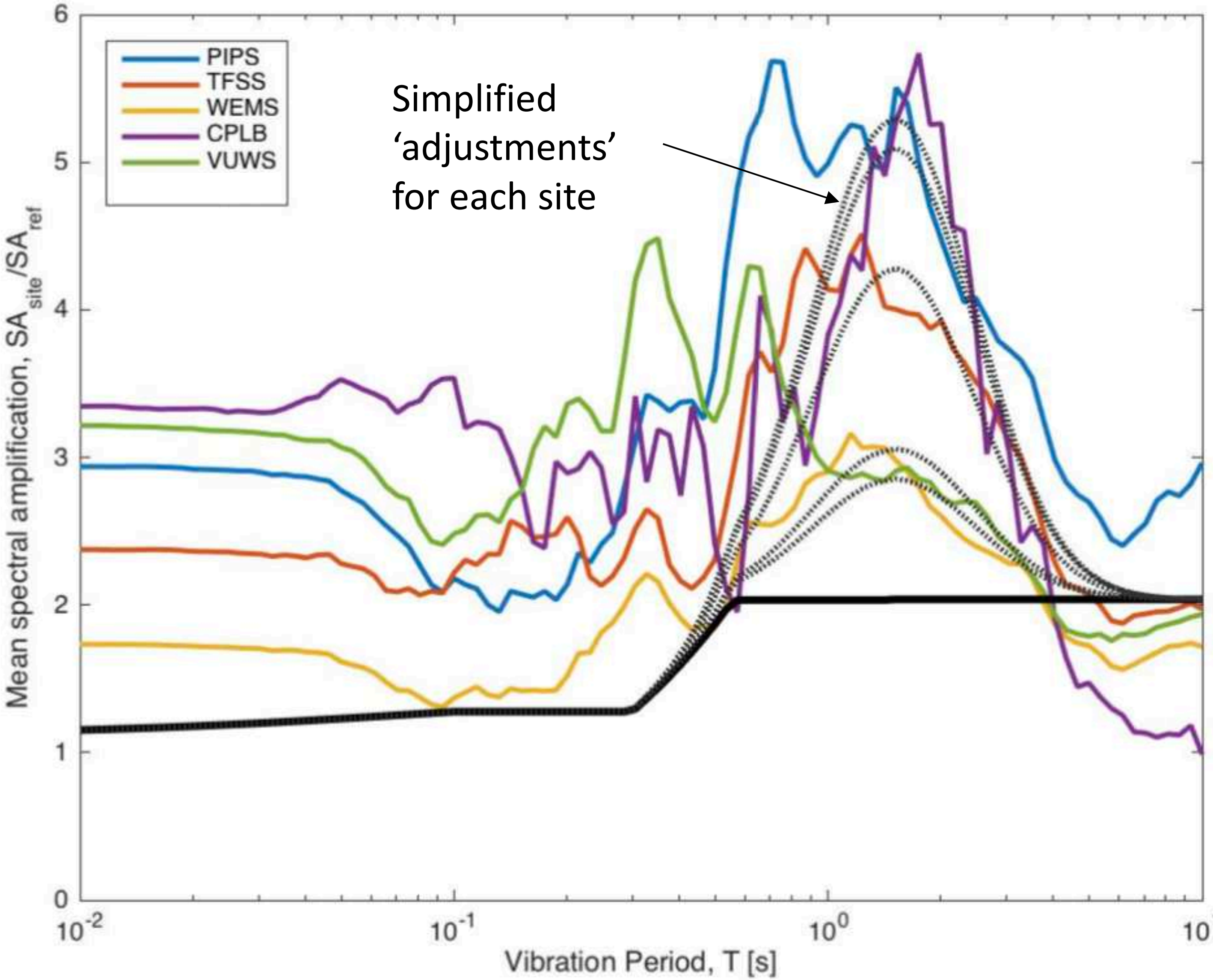




- 19 historical events with M>5
- Compared with site class D spectra

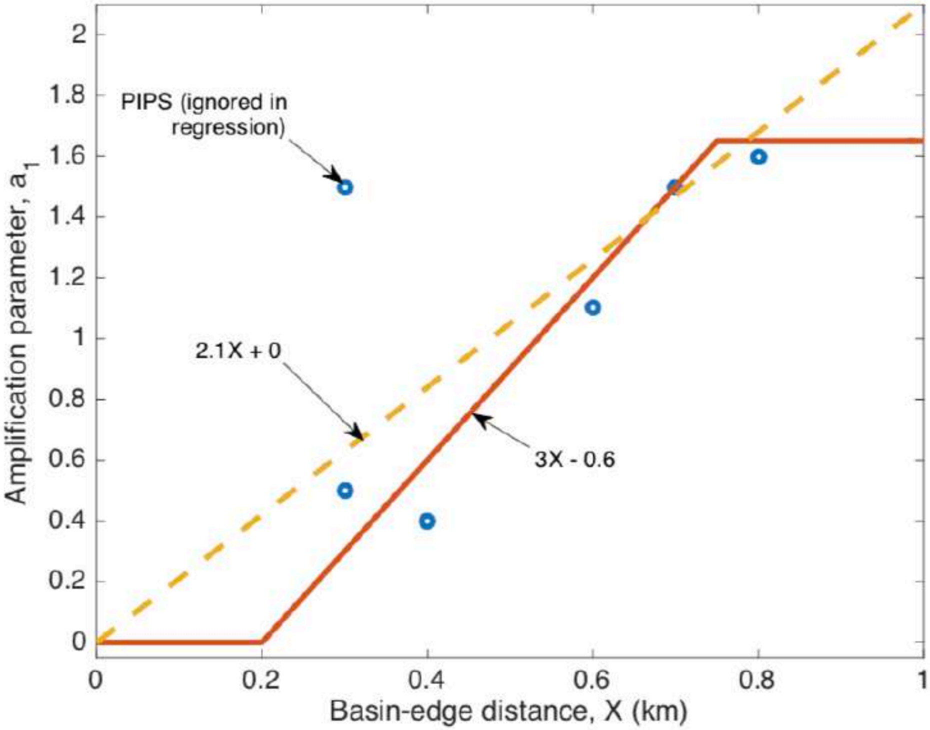
(Bradley et al, in prep)

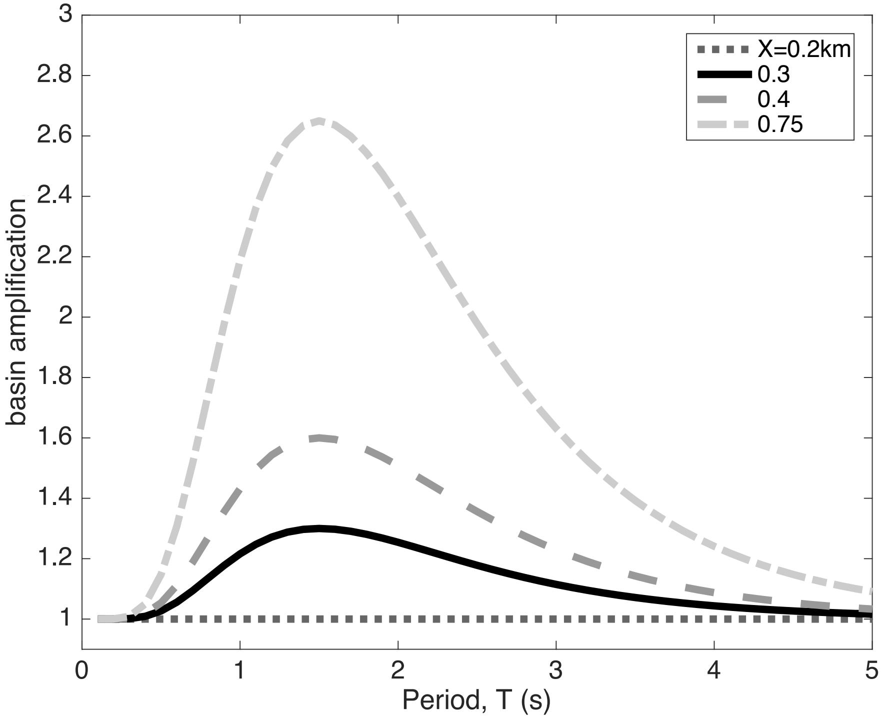
Code-oriented empirical adjustment



(Bradley et al, in prep)

Code-oriented empirical adjustment





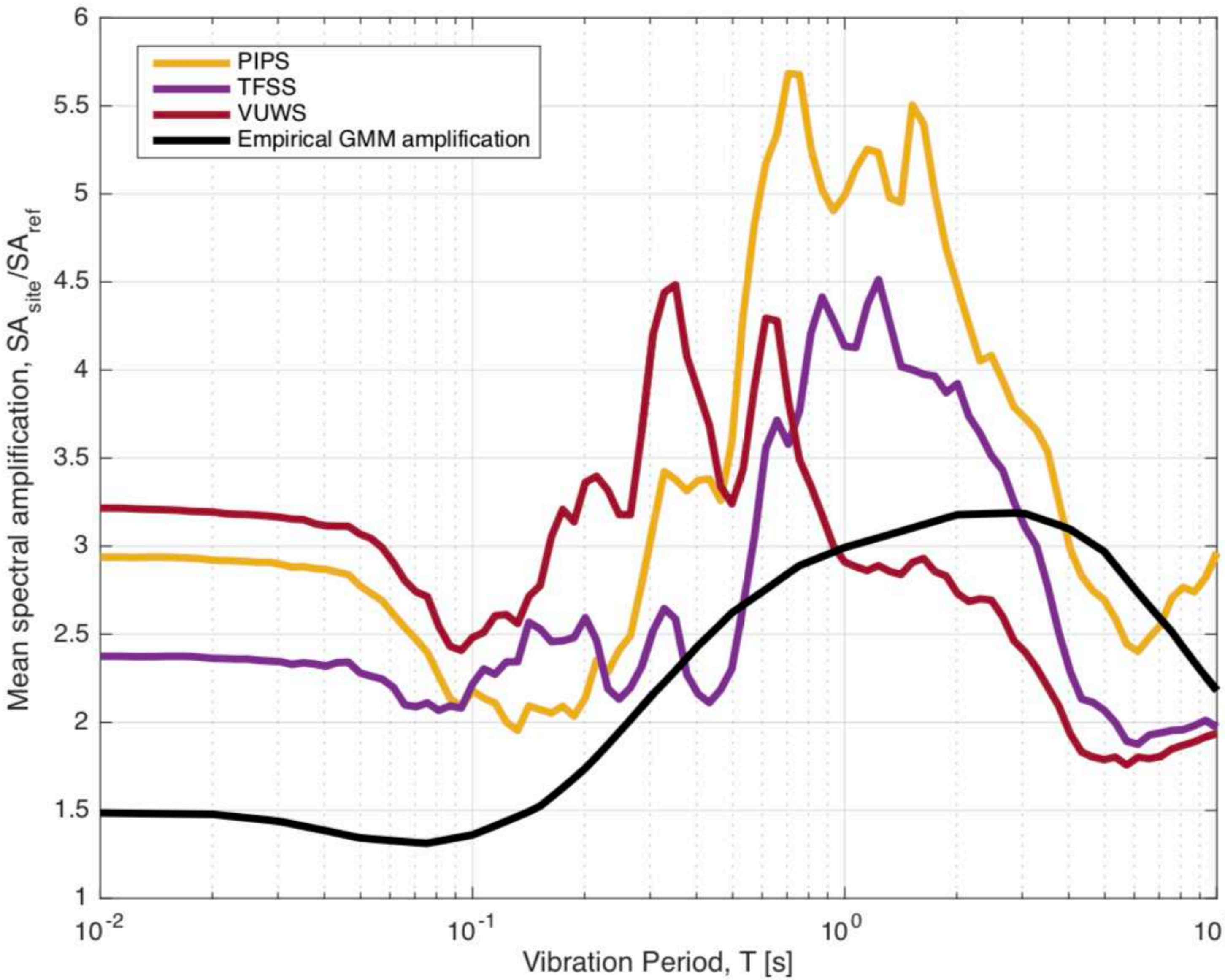
Empirical adjustment that is a function of:

- Distance from basin edge (Waterfront is ~0.5-0.7km)
- Vibration period (largest at T=1.5s)

(Bradley et al, in prep)

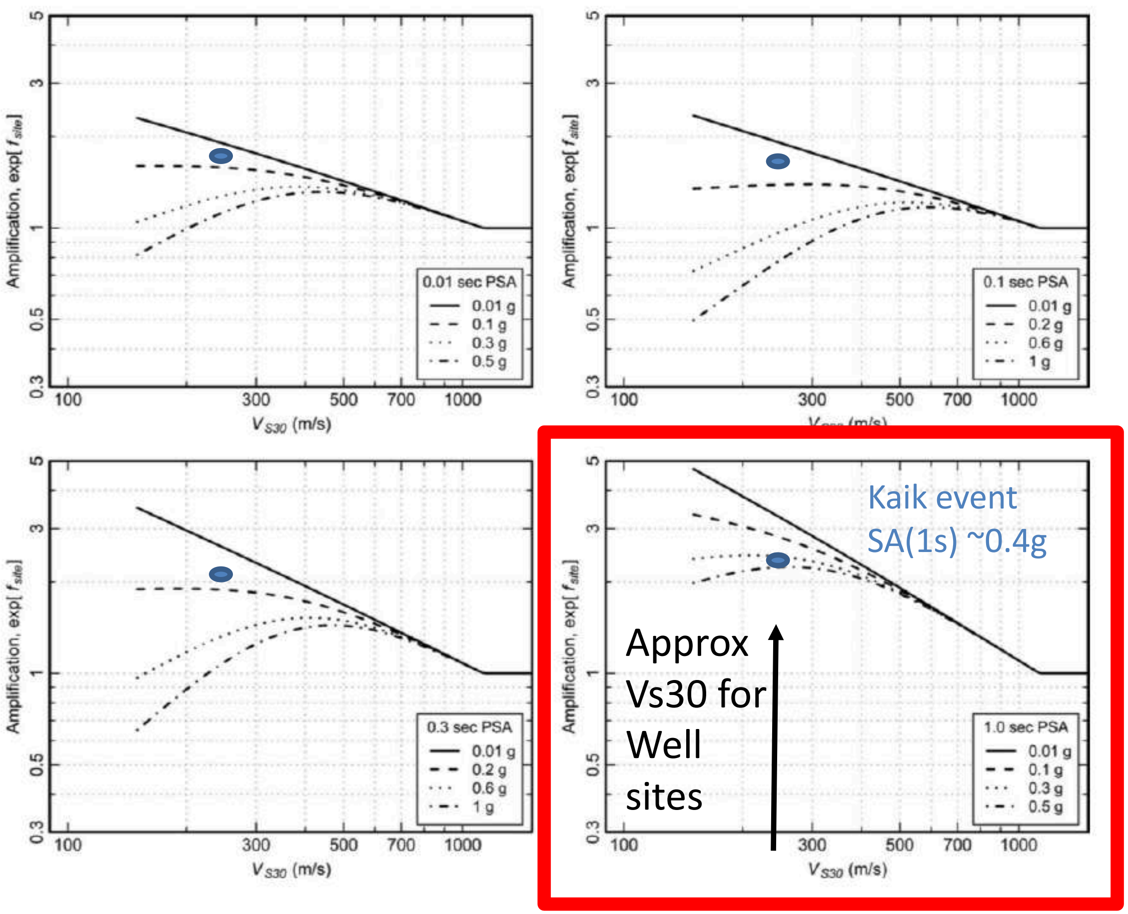
What do empirical ground motion models tell us?

Comparison with empirical ground motion models



Comparison with empirical ground motion models

Empirical perspective on nonlinear effects



- In Kaikoura event SA(1s)~=0.4g
- Design SA(1s) for site class D = 0.75g.
- Nonlinearity effect decreases with increasing amplitude

(Chiou and Youngs, 2008)

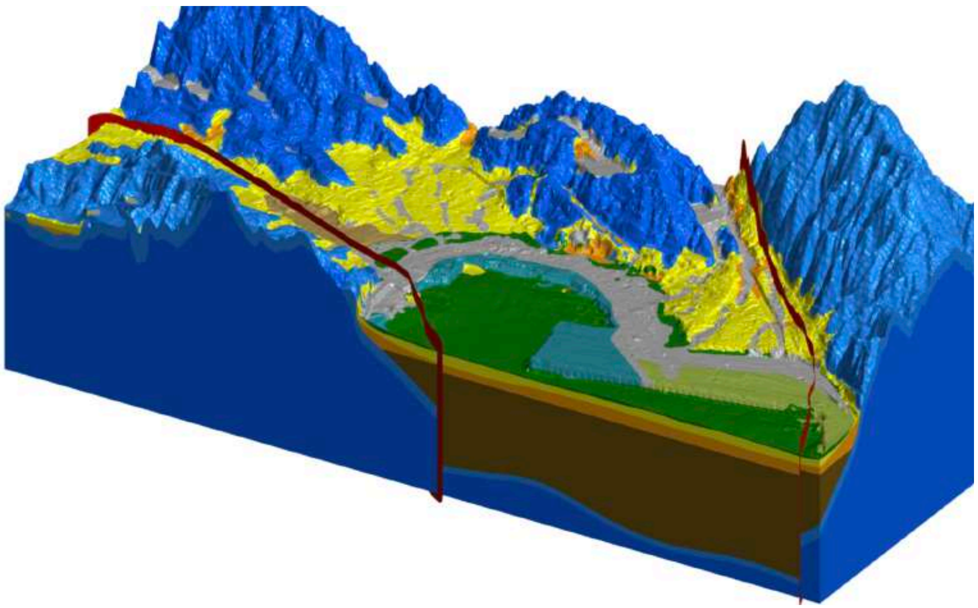
The use of physics-based simulations

Physics-based representation

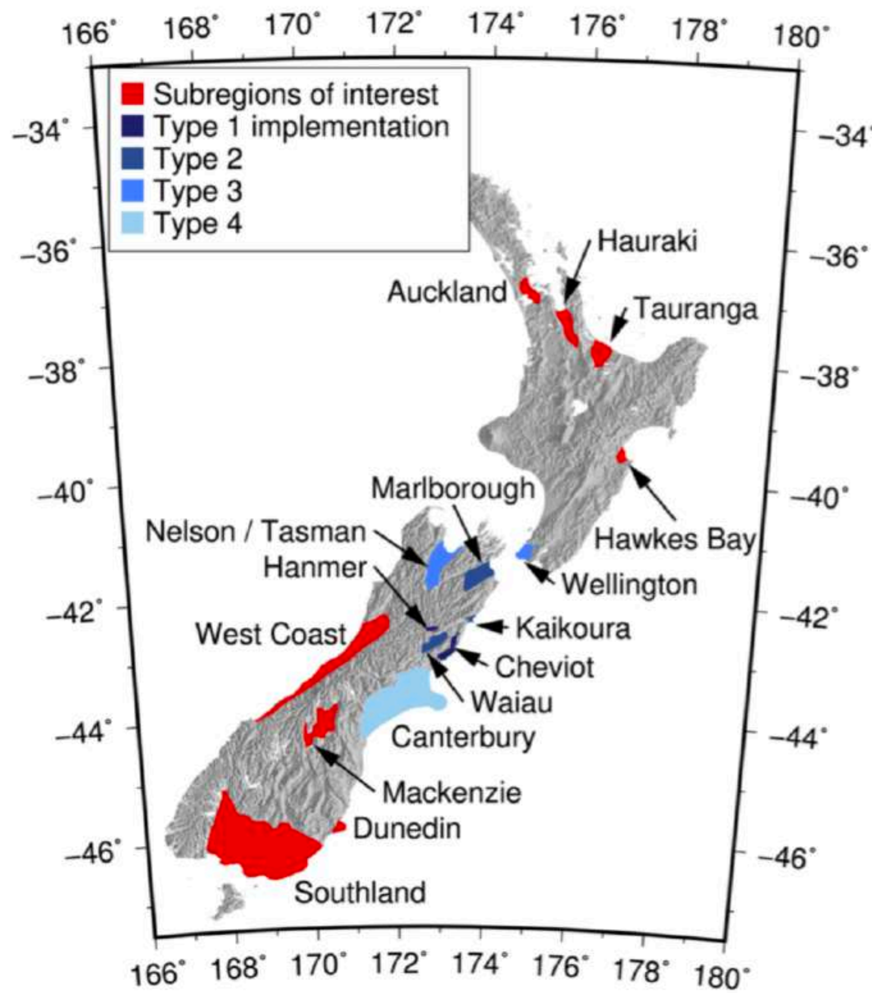
- Limitations of empirical approach
  - What to do for other regions of NZ (many of which are located in sedimentary basins)?
  - Interaction of the basin 3D geometry with the source location (back-azimuth)
  - Effects that are not seen in the observational data, specifically in Wellington, associated with larger magnitude events (longer duration of shaking/resonance, nonlinear surficial soil)

Explicit modelling of sedimentary basins

Wellington and NZ-wide

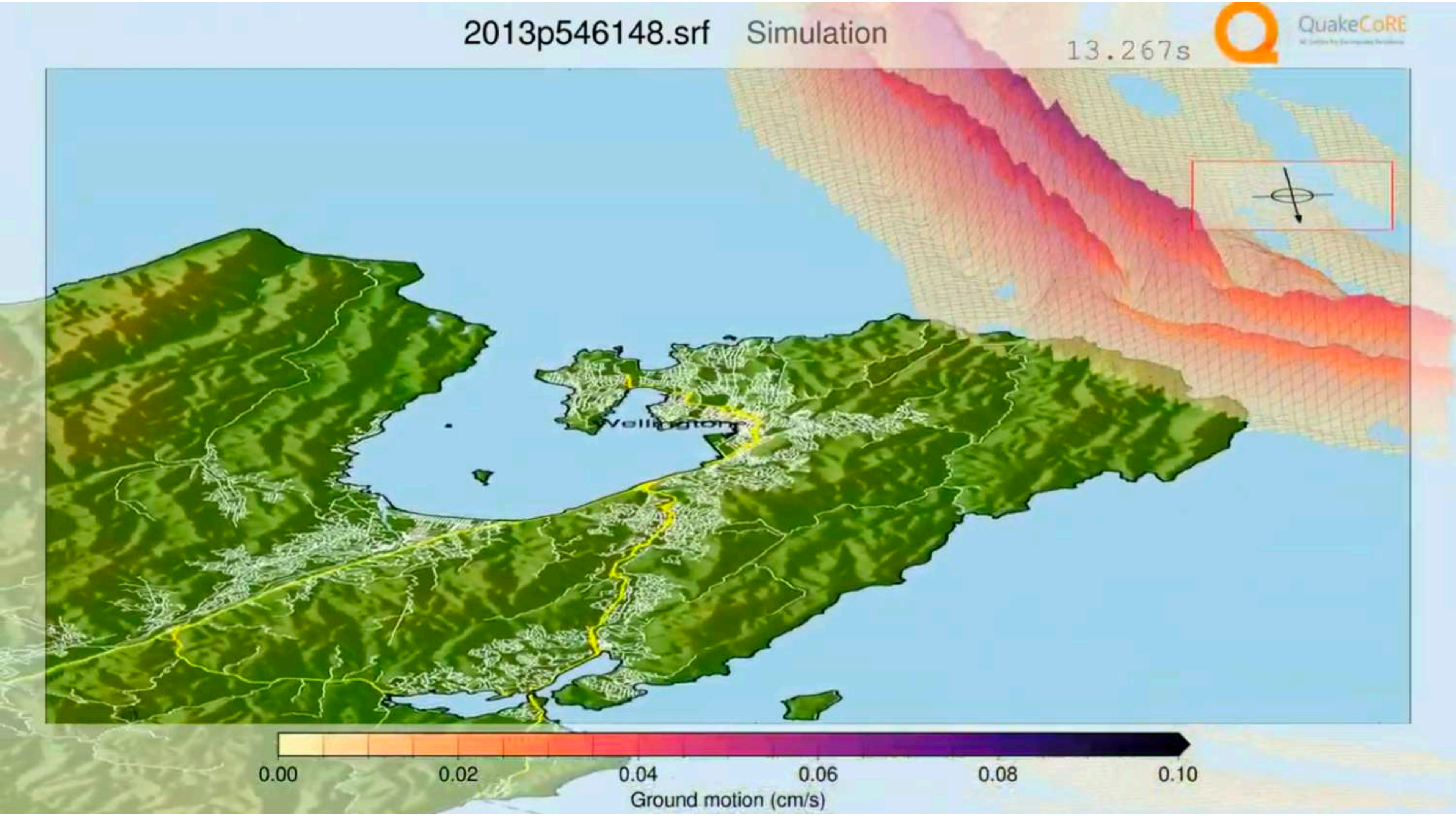


(Kaiser et al, 2019)



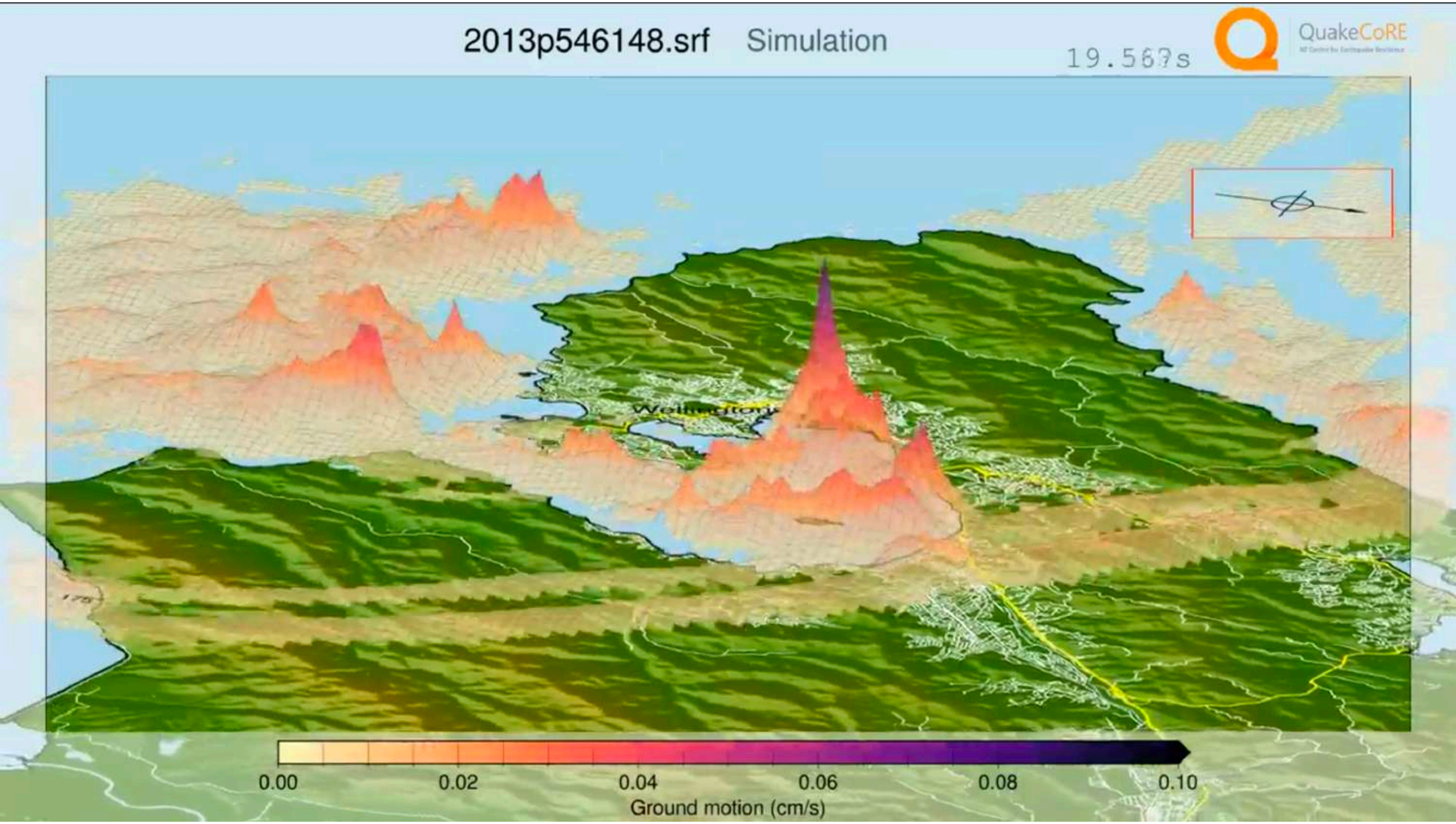
(Thomson et al, 2020)

Example simulation of historical event



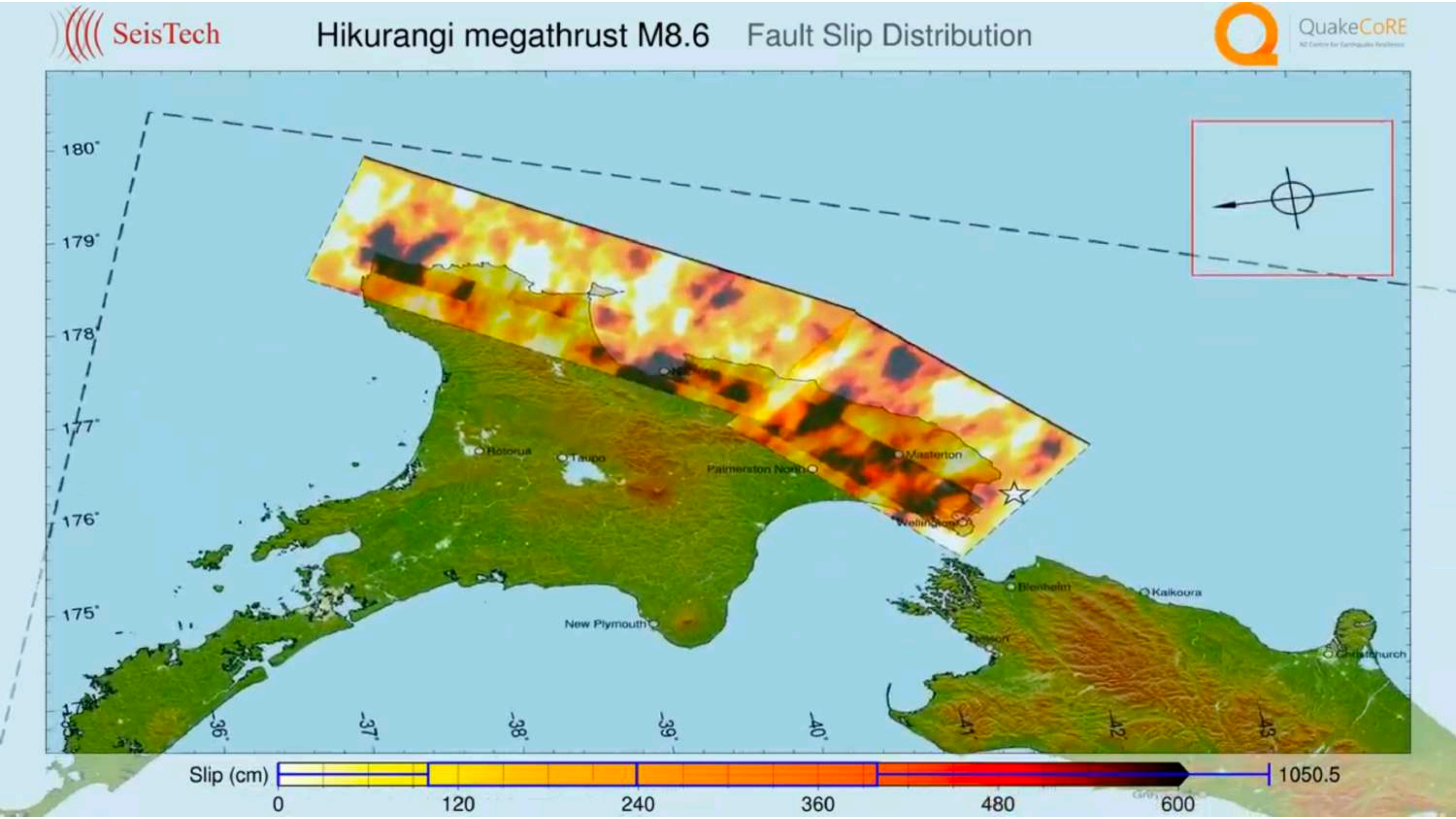
Video here: https://www.youtube.com/watch?v=kDJn9bMEQo8

Example simulation of historical event



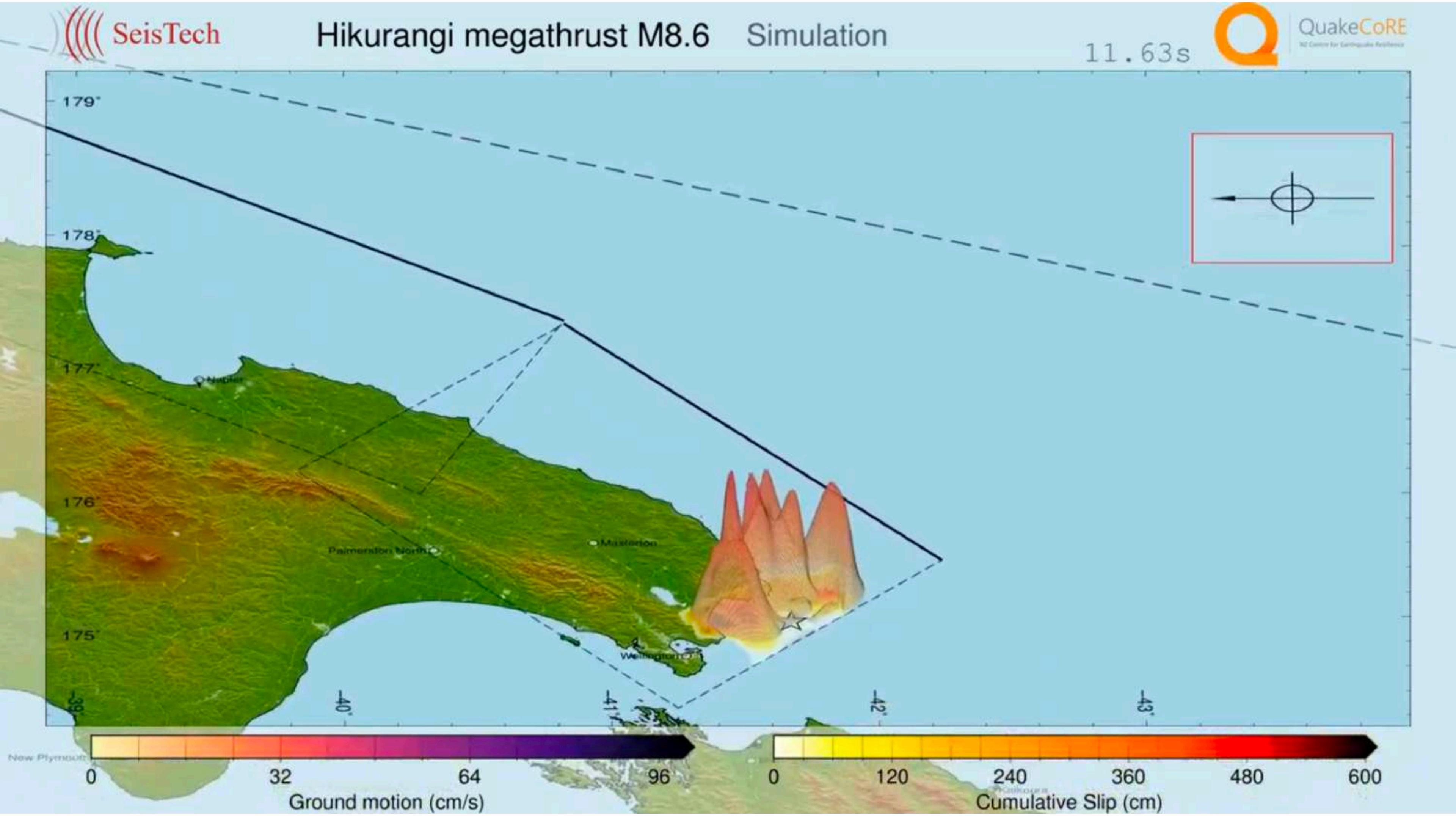
Video here: https://www.youtube.com/watch?v=kDJn9bMEQo8

Example simulation of Hikurangi rupture



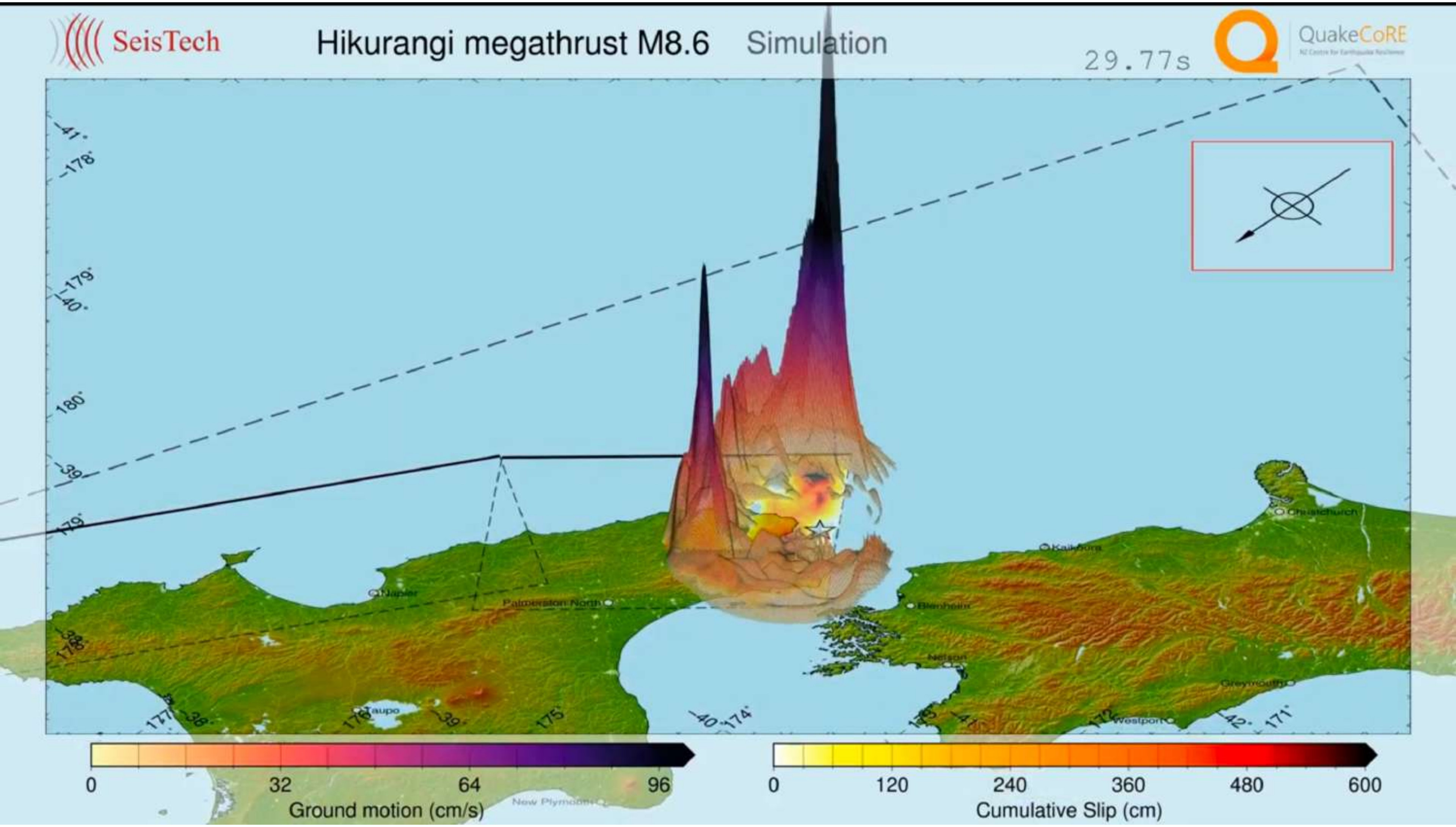
Video here: https://www.youtube.com/watch?v=55RhqF7xc78

Example simulation of Hikurangi rupture



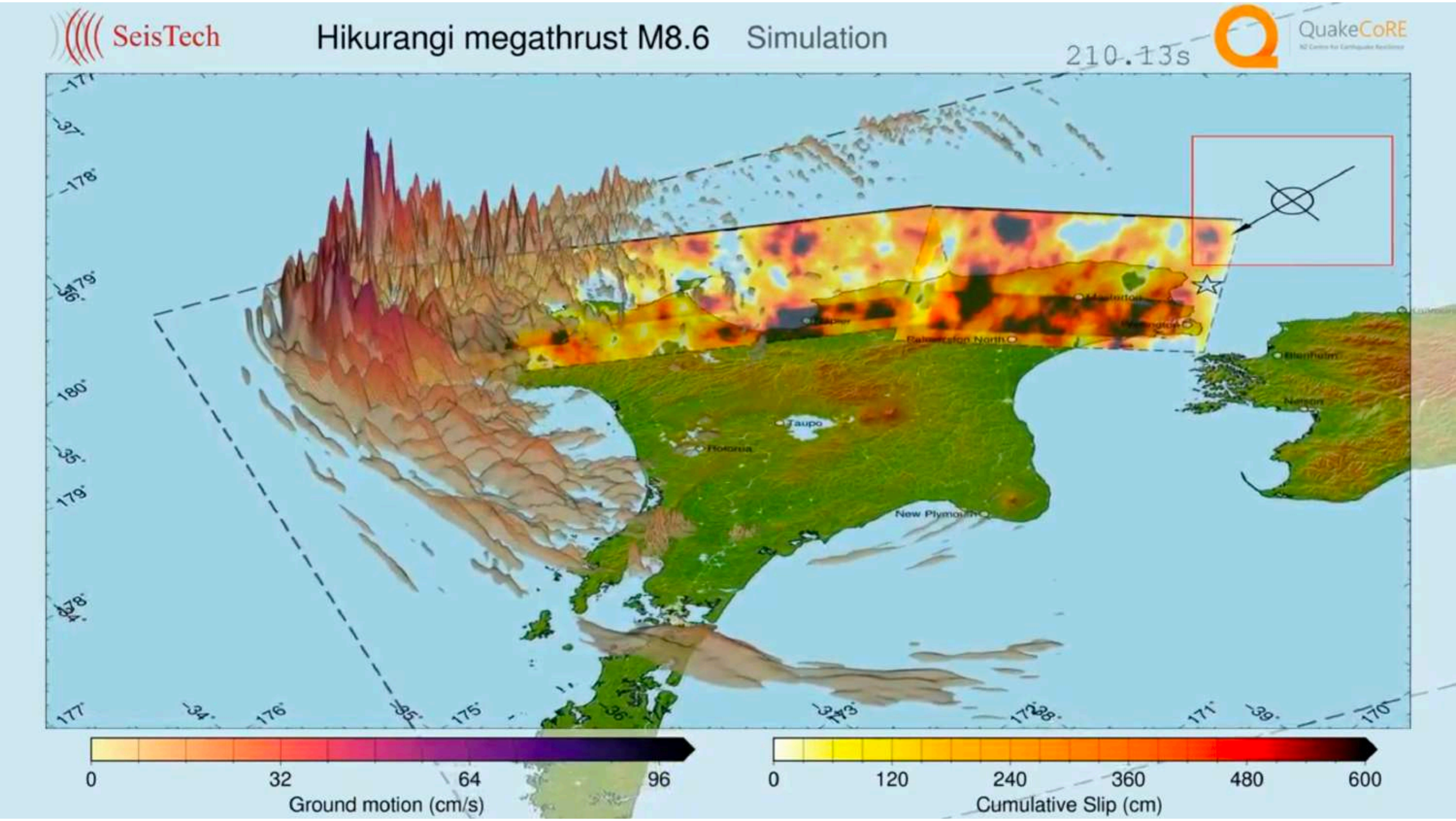
Video here: https://www.youtube.com/watch?v=55RhqF7xc78

Example simulation of Hikurangi rupture



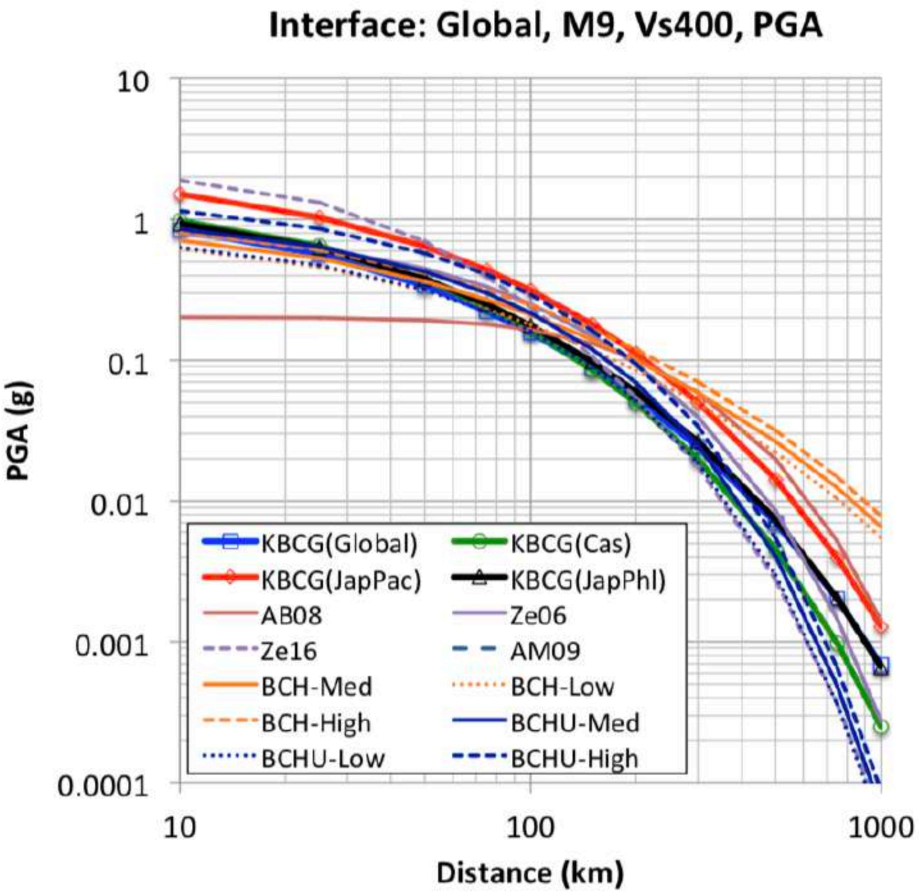
Video here: https://www.youtube.com/watch?v=55RhqF7xc78

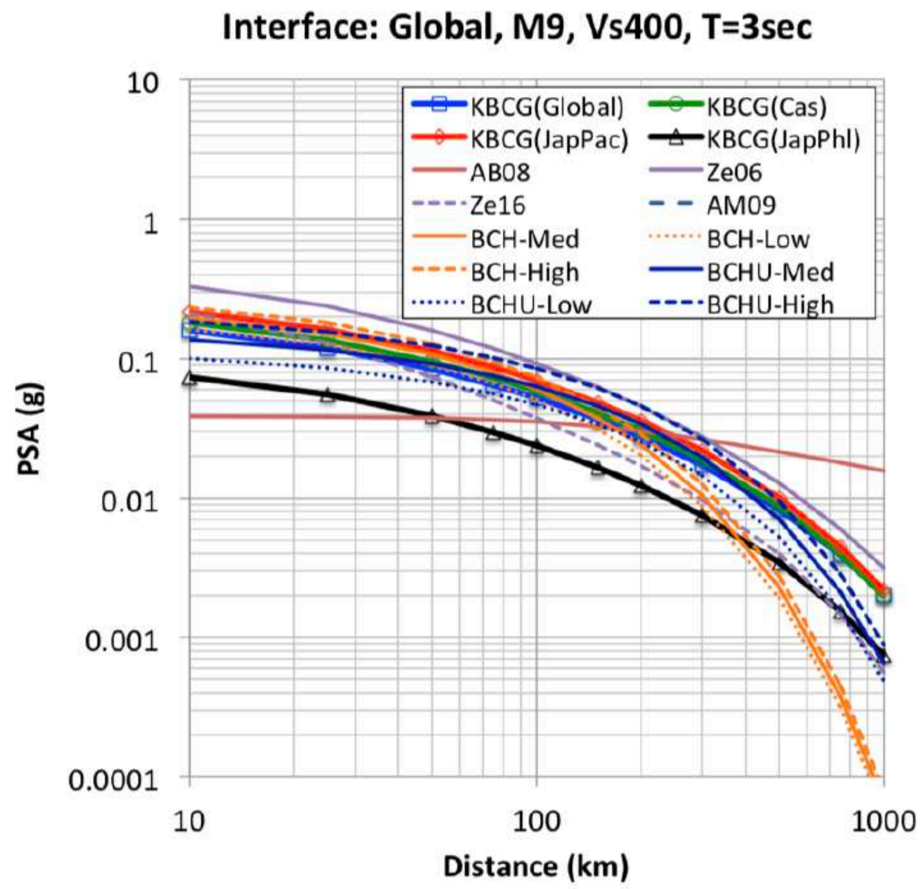
Example simulation of Hikurangi rupture



Video here: https://www.youtube.com/watch?v=55RhqF7xc78

Using simulations to constrain empirical ground motion model 'extrapolation'





(Kuehn et al, 2020)

Conclusions (1/2)

The 2016 Kaikōura earthquake highlighted the significant amplifications of ground motion over short distances due to near-surface soils and 'basin' effects

- 'Basin' effects comprise both amplification due to impedance (from stiff to soft soils), as well as 'edge' effects associated with refraction and critical reflection at the basin edge
- These effects have been seen systematically in major historical earthquakes internationally, as well as in New Zealand, and are supported by simulation evidence
- They are a geometric problem and therefore are repeatable (with some level of 'variation' due to complexities in the phenomena)
- They also will be present in all sedimentary basins in NZ – the specific impact will depend on:
  - (i) the stiffness of the sedimentary soils [i.e. the impedance ratio];
  - (ii) the geometry (including depth) of the basin.

  Which will influence the degree of basin amplification, and the vibration periods where it is most pronounced.

Conclusions (2/2)

Accounting for basin effects in seismic hazard and design, going forward

- Adjustment factors for design codes/standards to reflect first-order features of differences between observations and present code/standards
- Use of site-specific studies that can model these effects explicitly
- Increasing role of simulations to supplement/replace empirical methods of ground motion prediction to advance scientific understanding
- Science feeds into revised seismic hazard analyses nationwide that can underpin updates to codes/standards

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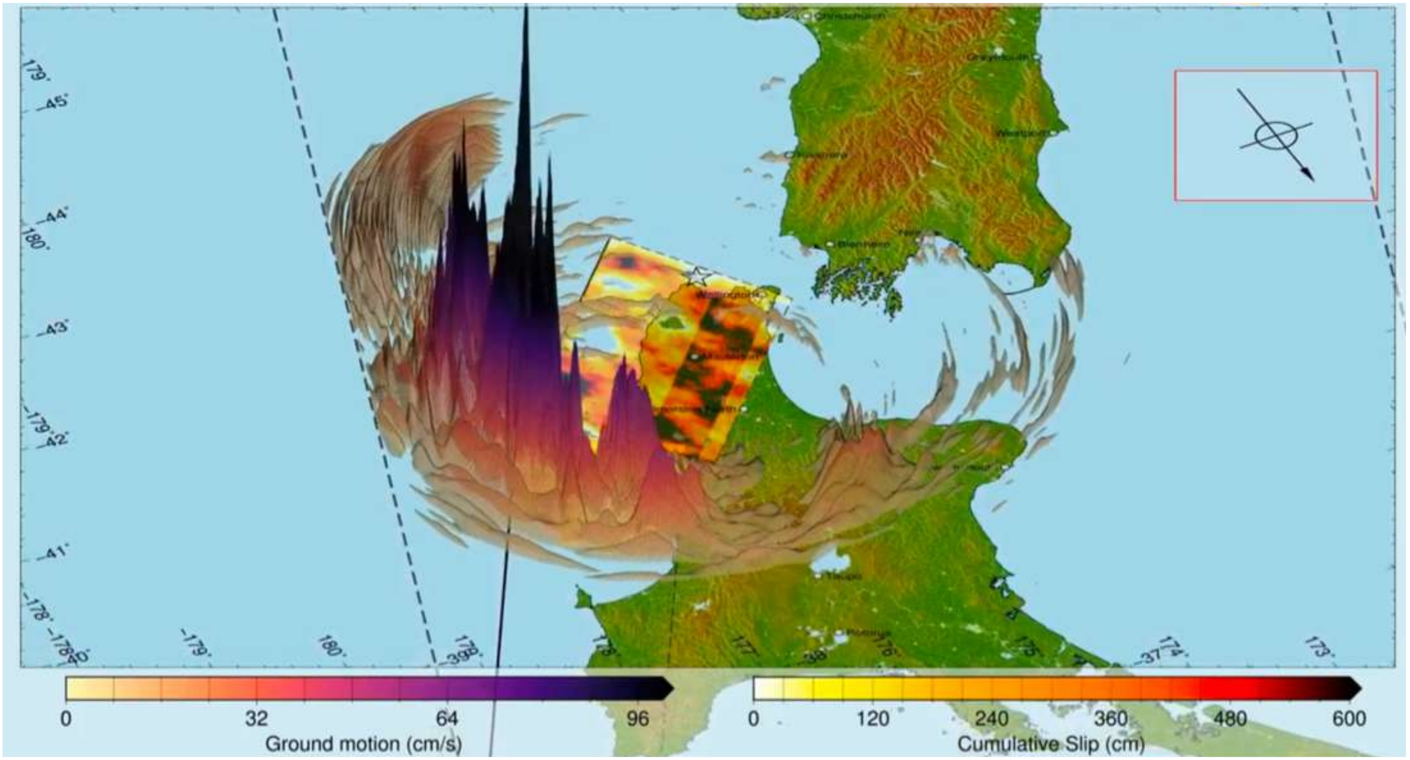

Thank you for your attention

https://sites.google.com/site/brendonabradley/

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EQC

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